Electromyographic analysis of covert responses during global and selective stop-signal tasks: implications for theoretical models of stopping behaviour.

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Statement of Sources

I declare that this report is my original work and that contributions of others have been duly acknowledged.

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Anna Read Date

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Abstract

The current study investigated inhibitory control mechanisms and models of action cancellation. Twenty-five participants (9 male) aged between 19-40 years (*M*=23.96, *SD*=4.50) responded to a visual 'go' cue by depressing stiff or compliant buttons with their index fingers (bimanual Go task). On 30% trials, a stop-signal required countermanding of the left, right or both responses (i.e., selective or global stopping). Electromyographic (EMG) analysis determined the nature of responses in each hand, and enabled covert muscle activity (partial response) to be observed in successful stop trials. Significantly, more partial responses were observed with the stiff compared to the compliant button, and also led to degraded inhibitory control as indicated by longer stop-signal reaction times. Moreover, the presence of these partial responses challenges the assumptions of the traditional horse race model of inhibitory control, indicating that the go and stopping processes interact with one another prior to, and following, the initiation of the go response. The method employed to assess partial responses detected many more partial responses than the previous literature, indicating the utility of the technique for future research, which could aim to develop our understanding of inhibitory control across the lifespan from both a behavioural and computational modelling perspective.

In the preparation and execution of motor action, the human motor system is critical for making rapid decisions and selecting the correct response in order to navigate our surroundings and complete essential tasks (Logan, Cowan, & Davis, 1984). The motor system is also required to inhibit incorrect responses when we are made aware of them (Duque, Greenhouse, Labruna, & Ivry, 2017), or when cancelling and re-programming of an alternative action is required based on altered (updated) environmental cues or stimuli. Inhibition involves a rapid control mechanism that aims to countermand the execution of a response, and this mechanism then interacts with slower, bottom-up, processes to adjust and monitor the ongoing performance (Verbruggen & Logan, 2008). Inhibitory deficits are implicated in a number of conditions including attention deficit hyperactivity disorder, obsessive compulsive disorder, (Aron, 2011) and Tourette's Syndrome (Verbruggen & Logan, 2008), as well as in healthy ageing (Fujiyama, Hinder, Schmidt, Garry, & Summers, 2012). It is therefore important to understand the mechanisms of inhibitory control—such understanding may ultimately lead to better treatments or interventions to assist those with inhibitory deficits.

Inhibition falls into two main categories: global and selective. Global inhibition involves the cancellation of *all* volitional movement following a stop signal presented shortly after the 'go' stimulus, while selective inhibition involves interrupting one component of a movement while continuing with another (Duque et al., 2017). There is uncertainty around the underlying mechanism of global inhibition. Some researchers suggest that the 'go' and 'stop' components are represented by independent processes that "race" until they reach a *point of no return* (Logan, 1981; Logan & Cowan, 1984; Osman, Kornblum, & Meyer, 1986), at which point the action is either executed (go wins) or countermanded (stop wins). In contrast, some researchers suggest that the 'stop' and 'go' processes interact with one another prior to, and following, the initiation of a response (McGarry & Franks, 1997). Selective

inhibition also has a number of different models purporting to explain the mechanisms of the process. One suggestion is a non-selective global braking followed by a rapid reprograming of the appropriate (continuing) response (Coxon, Stinear, & Byblow, 2007). However an alternative, model-based, description suggests that a selective response requires evidence accumulation to reach a higher threshold prior to the action being initiated, and that evidence towards the global response fails to accumulate to reach this higher threshold (MacDonald, McMorland, Stinear, Coxon, & Byblow, 2017). Based on both of these models, a selective stop requires more time to execute than a global stop (Coxon et al., 2007; MacDonald et al., 2017).

The current research used electromyographic (EMG) recordings of muscle activity to investigate the mechanisms of inhibitory control in both global and selective stopping. The analysis enabled covert responses, that is muscle activity time-locked to visual stimuli but which did not result in overt responses (i.e., the response button was not pressed), to be investigated in successful stop trials, providing evidence for or against the contrasting theoretical models of stopping behaviour. The following section will include a review of the relevant literature around global and selective inhibition and the models and mechanisms that are believed to explain these processes, as well as a summary of the stop-signal task and the use of EMG to measure covert muscle activity.

Literature Review

Global inhibition. Global inhibition is the stopping or cancellation of a complete action, and is an important indicator of general executive control (Verbruggen & Logan, 2008). This type of inhibition may be employed when driving, for example, if a child ran out onto the road soon after your foot had moved toward the accelerator, in order to cancel the movement and prevent disaster. Global inhibition would also be employed more commonly,

for example when resisting another slice of cake, or quickly inhibiting a sentence when another person starts talking at the same time.

Voluntary motor actions are predominantly controlled by the contralateral primary motor cortex (M1), which integrates all relevant information about visual and sensory stimuli (Stinear, Coxon, & Byblow, 2009), in order to make the best decisions about the correct motor response to execute. Particularly relevant is the ability of M1 to make rapid decisions; taking information about the environment to execute fast responses to stimuli (Cowie, MacDonald, Cirillo, & Byblow, 2016). The ability to cancel a planned movement (response inhibition) involves the cortico-basal ganglia network (Duque et al., 2017), and is a critical attribute of normal human motor control. This network involves the right inferior frontal cortex, dorsomedial frontal cortex, and the basal ganglia (Duque et al., 2017; Wessel & Aron, 2017). The subthalamic nucleus of the basal ganglia transmits excitatory stimulation to the medial globus pallidus (GP), the GP therefore inhibits the motor thalamus, which decreases excitatory drive towards the motor cortex, ultimately stopping motor activity globally (Wessel & Aron, 2017). Inhibition is an internally generated act of control, produced by the higher order executive system in the brain, and allows self-regulation and the stopping of an action when it is rendered inappropriate for the present situation (Williams, Ponesse, Schachar, Logan, & Tannock, 1999). This may occur when sensory stimuli change rapidly, when new stimuli becomes available, or when the perception of existing stimuli changes (i.e., internal states change and therefore decisions about movements change) (van den Wildenberg et al., 2010). This peripheral system of inhibition globally blocks all motor commands, restricting any motor response (De Jong, Coles, Logan, & Gratton., 1990).

A number of theoretical models have been proposed to explain the process of global inhibition including the independent race model (Logan & Cowan, 1984), and a model of interacting processes (McGarry & Franks, 1997). Logan and Cowan (1984) took the

preliminary idea of a race model and developed it into a formal model describing a horse race between the 'go' and the 'stop' processes. Here, the 'stop' process is responsible for responding to subsequent stimuli (stop-signal) that signals inhibition (cancellation of the response process) should occur (Verbruggen & Logan, 2009). Despite the processes beginning at different time points (i.e., the 'go' process begins following the initial 'go' stimuli, while the 'stop' process begins on presentation of the subsequent stop-signal) they 'race' to a common finish line, or threshold for evidence accumulation, that results in execution of the winning process. That is, a 'go' response is executed, or the 'go' process is inhibited by the successful activation of the 'stop' response (Logan & Cowan 1984). Earlier research had suggested a *point of no return* exists, a point beyond which a physical (go) response that has already been engaged can no longer be prevented (Bartlett, 1958). Specifically, even if the stop response reached the finish line following initiation (but not full execution) of the 'go' response, countermanding would not be possible. In combination with the horse race model, this interpretation suggests that movement execution is a ballistic process, which is fully completed once it has been initiated, and is therefore often unable to be inhibited (Verbruggen & Logan, 2009). The time window in which the race between the production and inhibition processes occurs must therefore be a controlled period during which changes can be made to actions, until the ballistic process begins, at which point inhibition can no longer be employed (De Jong et al., 1990). The point at which the ballistic process begins is thus deemed the *point of no return* (Bartlett, 1958), and this interpretation would suggest that the process of inhibition is an all or nothing system.

Despite the appeal of this theoretical model, evidence in favour of a truly ballistic process in inhibitory control is scarce (Ko, Alsford, & Miller, 2012) with the majority of research focusing on the behavioural responses rather than physiological evidence (McGarry & Franks, 1997). However, the behavioural data alone cannot discriminate between ballistic

and non-ballistic processes, and physiological data is required to enable investigation of the underlying processes of inhibition. Research by Coles, Gratton, Bashore, Eriksen, and Donchin (1985) used dynamometers to measure force of squeezing while responding to a flanker task. They identified muscle activity via dynamometer squeezes that did not reach the threshold required for the squeeze to register a response (Coles et al., 1985), which indicates that muscle activity associated with the response can occur prior to the response being cancelled. This suggests that the go and stop (cancellation) processes may not be independent, and instead may interact; however this evidence is behavioural in nature, and therefore cannot elucidate where the ballistic and non-ballistic processes begin and end.

More recent research has instead used electromyography (EMG) to measure muscle activity during tasks investigating inhibitory control, which provides physiological evidence of the inhibitory processes (e.g. Ko et al., 2012; McGarry & Franks, 2003; Servant, White, Montagnini, & Burle., 2015). This technique allows researchers to detect covert muscle activity that does not result in an overt response to the task (van den Wildenberg et al., 2010), such as a button press, thus providing an additional insight into inhibitory control than behavioural outcomes alone. This evidence challenges the notion of a point of no return, suggesting that the inhibitory process is not discrete (i.e., the only options going or stopping), but instead inhibition can occur at the very end of that physical process, even after motor units have been activated (McGarry & Franks, 1997). Incomplete response patterns that do not result in overt behavioural responses (i.e., button presses) have been termed "partial responses" (De Jong et al., 1990; McGarry & Franks, 2003). McGarry and Franks (1997) suggest that partial responses are evidence of leakage from the response production process, and are the result of imperfect stopping. Partial responses provide evidence to challenge the previously held assumptions that muscle activity only occurs once a decision threshold has been made (Logan & Cowan, 1984), as partial responses indicate that the response can still

be cancelled after muscle activity begins. Servant et al. (2015) posited an alternative interpretation of a partial response, suggesting that there are two "thresholds" for evidence accumulation—the first (lower) one signaling the muscle activity to begin, and then the final threshold beyond which the movement can no longer be stopped. During the period between the thresholds, the response can still be canceled, which explains the presence of muscle activity prior to the response being inhibited (Servant et al., 2015). By measuring partial responses, the mechanisms driving global inhibition can be investigated.

Selective inhibition. While global inhibition involves the complete stopping of a movement, selective inhibition is the process of interrupting one movement while continuing another (Coxon et al., 2007), for example if you were walking and talking on the phone, and then had to stop to wait for a car to pass before crossing the road, you could employ selective inhibition to continue speaking on the phone. While global inhibition is more likely to be tested in laboratory settings, selective inhibition is more likely to be employed in everyday movement (Majid, Cai, George, Verbruggen, & Aron, 2012): most of the movement engaged in daily life requires each side of the body to move slightly differently, it is unusual that they will move in synchronisation (Welniarz, Dusart, Gallea, & Roze, 2015).

Movements that require only one hand (unimanual movements) involve activation of the contralateral (opposite hemisphere) motor cortex (Welniarz et al., 2015), however it has been suggested that the motor cortex naturally enacts movements bimanually (using both sides of the brain equally) (Cincotta & Ziemann, 2008). To allow unilateral movement, where only one side of the body is involved in a movement, or each side is moving independently, an important feature of motor control is the ability to prevent information crossing into the contralateral hemisphere (the opposite hemisphere) via the corpus callosum (Welniarz et al., 2015). The mechanism required to both prevent the activation of the ipsilateral motor cortex

as well as allow unilateral movements is interhemispheric inhibition (IHI), and this mechanism declines with age (Fujiyama, Hinder, & Summers, 2013). Without IHI, movements can become synchronised, often resulting in "mirror movements", where the opposite limb moves in a similar way as the limb involved in a movement (Welniarz et al., 2015).

While global inhibition is generally assumed to involve a global braking of all movement (De Jong et al., 1990), there are a number of different hypotheses about the mechanisms of selective inhibition. Researchers initially believed that selective inhibition involved a central, cortical mechanism that delays the inhibitory response until it is made clear that inhibition is required, at which time the peripheral inhibitory mechanism is engaged (De Jong, Coles, & Logan, 1995). However, subsequent research found evidence to support an alternative hypothesis. This model suggests there is a generic, non-selective braking of the motor system by the basal ganglia when any stimulus signals that stopping is required, followed by a rapid reprogramming and execution of the unimanual response that is required (Coxon et al., 2007; De Jong et al., 1995; Xu, Westrick, & Ivry, 2015). Selective inhibition often results in a delayed response of up to 100ms compared to tasks that require no inhibition (Coxon et al., 2007), and this can be explained by the alternative hypothesis, as the two part process (with reprogramming) would result in longer processing times. This length of time is not long enough for the reprogrammed response to be an independent response, as the average latency period required for simple reaction time (RT) tasks is at least 200ms (Woods, Wyma, Yund, Herron, & Reed, 2015). Therefore, it is more plausible that the processes are related, with the delay potentially due to a higher threshold of information required for a selective response as compared with a global response (MacDonald et al., 2017). The activation threshold model posits that the initial global braking automatically raises the threshold required for a response, which cannot be reached by the global response,

and therefore requires additional information to execute the selective response (MacDonald et al., 2017).

Based on the finding of a delayed response associated with selective inhibition (MacDonald et al., 2017), is could be assumed therefore that there is a cost associated with selective inhibition—a slowing of responses and a higher probability of responding incorrectly (Coxon et al., 2007). However, some researchers have suggested that this cost can be reduced with appropriate cognitive cues. For example, Majid and colleagues (2012) found that selective stop delays can be reduced if participants are forewarned that stopping will occur, and Xu and colleagues (2015) suggested that delays can be minimised or even eradicated without forewarning. Specifically, while selective stop delays were found in many of the conditions in their experiment, selective stop delay minimisation was achieved in specific conditions in which the delay between the 'go' and the 'stop' was very short, and which used a compatible tactile cue after reward-based practice sessions (Xu et al., 2015). This led MacDonald and colleagues (2017) to suggest that despite these results, delays are inevitable, and therefore selective inhibition has an associated cost.

The stop-signal task. Initially developed by Lappin and Eriksen (1966), the stop-signal paradigm involves participants responding bimanually to a 'go' stimulus on a screen in an attempt to respond quickly, and on a small number of variable trials a 'stop' signal will also appear either at the same time or shortly after the 'go', to which the participant must try to cancel their response to original 'go' stimulus (Band, van der Molen, & Logan, 2003; Schmitt, Ankeny, Sweeney, & Mosconi, 2016). The time period between the 'go' and the 'stop' signals is the stop-signal delay (SSD), with performance on the task dependent on this delay, in combination with the individual's inhibitory control function (Logan, 2015). The probability that a participant will stop correctly on the stop-signal task can be manipulated by

the timing of the presentation of the stop signal (Band et al., 2003). For a given level of inhibitory control, the probability of correctly stopping will decrease as SSD is increased, and vice versa.

According to the horse-race model of inhibition (Verbruggen & Logan, 2009), performance on the stop-signal task can be modelled as a linear progression between the probability of failing to stop, as a function of the SSD period—the longer the delay period, the less likely successful countermanding (i.e., inhibition) will occur (Boucher, Palmeri, Logan, & Schall, 2007). Experimentally, the SSD can be set in two ways: fixed or dynamic. A fixed SSD means that the delay between the go and the stop signal is predetermined, and is randomly set at predetermined lengths of time throughout the experiment. A dynamic SSD means that the time is based on the previous response: if the participant successfully inhibits their response, the next stop-signal the SSD will increase in length making it harder to stop, and if they are unsuccessful in inhibiting their response, on the next stop-signal the SSD will decrease in length making it easier to stop (Logan, Schachar, & Tannock, 1997). This iterative method allows the experimenter to manipulate the stopping rate so that stopping successfully occurs 50% of the time, and this time period becomes the point at which the going and stopping processes of the horse race are "tied" (Logan et al., 1997).

The stop-signal task is useful as it provides a measure of stopping latency for each individual (Congdon et al., 2012), and therefore across the sample. By considering the individualised SSD, the stop-signal tasks allows estimation of stop-signal RT (SSRT): the latency of the inhibitory action, and a useful estimation of individual's inhibitory function (Verbruggen & Logan, 2009). The SSRT is not observable as it does not involve an overt button press, but rather is a measure of the internal processes, and it is therefore necessary to estimate it using the SSD. The RT for conditions in which no stop-signal is presented ('go' conditions) is equal to the SSD and the SSRT combined (Logan et al., 1997), and this

calculation is more reliable when the SSD is set at the centre of the distribution (i.e., when stopping occurs 50% of the time) (Band et al., 2003). Therefore, to calculate the SSRT, the SSD can be subtracted from the 'go' RT to determine the latency period of inhibitory action, and to therefore index inhibitory control.

The stop-signal task has been applied to a number of different inhibitory behaviours and muscles, including reaching tasks (Mirabella et al., 2012), elbow extensions (Kudo & Ohtsuki, 1998), eye movement tasks (Schmitt et al., 2016), and button press responses (Coxon et al., 2016). The general model of inhibitory control has been observed across all of these modalities and the stop-signal task is therefore assumed to be a robust method of measuring this model (Band et al., 2003). The stop-signal task has been modified to measure selective inhibition, where the task requires one part of the movement to be cancelled while another part continues to respond (Xu et al., 2015), for example stopping one hand while continuing to respond with the other hand. This tests the ability of the person to selectively stop a component of a bilateral task, therefore testing the ability of the left and right M1 to work independently, presumably through regulation of IHI mechanisms (Welniarz et al., 2015), which is a key attribute of human motor control.

Research by Ko et al. (2012) investigated inhibition during a global and selective stop-signal task, using force-sensitive buttons throughout the experiment to measure whether the amount of force participants used to respond depended on the presence of a stop signal. The results indicated that even when a stop-signal failed to prevent a response, these failed-stop responses were less forceful than the standard responses in which the stop-signal was not presented (Ko et al., 2012). The researchers suggested that this was due to the stop signals triggering an inhibitory effect, reducing the force, even though it was too late for response inhibition (Ko et al., 2012). They interpreted this as evidence that a final ballistic process beyond which motor control cannot occur does not exist, in line with McGarry and Franks'

(1997) earlier interpretation (Ko et al., 2012). This research followed on from earlier work which used a similar method of measuring force to investigate how individuals adjusted their executive control after they made an error (Burle, Franck, Bonnet, & Hasbroucq, 2002). These studies indicate how response force measurements can provide insight into the mechanisms of inhibitory control. To further investigate this, the current research aimed to use two different response force buttons to compare and how inhibitory control changes with a greater mechanical force requirement. If a point of no return did exist, it would be expected that the level of inhibitory control would not change between button types.

Electromyography. Electromyography (EMG) is a passive recording technique used to investigate muscle activity, and is particularly useful for investigating how the muscles involved in a physical response are executed (van den Wildenberg et al., 2010). Other neuroimaging techniques such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) have a number of issues including poor temporal resolution, low-signal to noise ratio (meaning that activity cannot be easily observed), and can be affected by noise from a range of sources (Servant et al., 2015). EMG, however, can be analysed on a trial-by-trial basis, making it a very powerful tool for understanding muscle activation patterns associated with inhibitory control (van den Wildenberg et al., 2010). Another benefit is that muscle activity can be observed and measured in a quantitative way even if it is not associated with a response, such as a button press (Servant et al., 2015) or a dynamometer squeeze (Smid, Mulder, & Mulder, 1990). Without EMG, these covert, "partial" responses would go undetected, and this measurement is a key component of the current research. In combination with the stop-signal task, EMG is able to detect covert muscle movement that still results in correct inhibition in response to a stop-signal, and therefore determine when partial responses occur during the task (Servant et al., 2015). Often, these partial responses

are unable to be detected by participants, with one study finding that less than one third of partial responses found in EMG evidence were detected by participants (Rochet, Spiecer, Casini, Hasbroucq, & Burle, 2013). The existence of partial responses challenges the assumptions of horse race models of inhibition (McGarry & Franks, 1997) that suggest that engagement of the muscles only occurs after the threshold of activity (point of no return) is reached, as partial responses show that motor activity can occur even when the overt response does not occur (Servant et al., 2015). This indicates the utility in EMG technology to reveal subthreshold impulsive actions that do not reach the level required to elicit a complete motor response, and are able to be suppressed (van den Wildenberg et al., 2010).

Exploration of the role of antagonist muscles in inhibition. The current research sought to explore the mechanisms of response inhibition. When measuring muscle movement, previous research generally measures the agonist, flexor muscle to determine when movement is occurring without the presence of a response, such as the FDI muscle for the index finger (e.g. Cowie et al., 2016; Jahfari, Stinear, Claffey, Verbruggen, & Aron, 2010; MacDonald et al., 2017) . However, a novel perspective in this research was to determine whether antagonist movements can provide insight into the specific mechanisms of inhibition: whether inhibition is a cancellation of the movement or if it is an independent, opposing movement. Therefore, this research aimed to measure extensor muscle activity of the index finger, as well as flexor activity, to provide electromechanical evidence for one process.

Aims and Hypotheses

The current research explored inhibitory processes, including the mechanisms and the models that are associated with them, and the costs and benefits of global and selective

inhibition. The research sought to ascertain whether a model of independent processes or a model of interacting go and stop processes can better explain the neural processes of global inhibitory control, and whether selective inhibition is a two-part process involving a global stop followed by the correct response, or whether another model may more accurately reflect the observed data. By using two different response buttons with different force requirements to register an overt response, the research aimed to determine whether having a stiffer button would lead to better inhibitory control.

It was hypothesised that the stiffer button would result in improved inhibitory control, if assumed that the going and stopping processes interact before and after the point of no return, rather than being independent processes. Further, the stiffer button would result in more partial responses, and longer Go RTs, than the compliant button, as well as a longer stop-signal RT (measure of inhibitory function). It was also hypothesised that on correct selective inhibition trials, partial responses would occur in both hands prior to the correct unimanual response being executed, as this would suggest a two part process of selective inhibition: a global braking followed by a reinstatement of the correct response, or an activation threshold model. We therefore expected a RT cost associated with selective stopping as compared to bimanual responses, due to the extra time required for a selective stop, as explained by the activation threshold model.

Method

Participants:

Twenty-five participants (nine male) aged between 19 and 40 years (M=23.96, SD=4.50) undertook the experiment which constituted a single session of ~ 2 hours which had received ethical approval from the Tasmanian Human Research Ethics Committee (Appendix A). Twenty-four participants were right handed (mean laterality quotient=0.84,

SD=0.17) and one was left handed (laterality quotient=-0.80) as determined by the Edinburgh Handedness Inventory (Oldfield, 1971; Appendix B). Participants were screened for neurological impairments, muscular conditions that limited their ability to comfortably undertake the task, and colour blindness (Ishihara, 1972; Appendix B/C). Participants were provided with a verbal briefing and information sheets (Appendix D) and then gave their informed consent (Appendix E) prior to beginning the study.

Materials:

Electromyography. EMG was recorded via adhesive electrodes positioned in a belly-tendon montage on the first dorsal interosseous (FDI) muscle of each hand with a ground electrode positioned on the wrist. The muscle was identified by having the participant isometrically abduct their index finger to engage the muscle. This muscle was chosen as a task-relevant muscle (agonist) as it also serves as an index finger flexor in volitional button presses. Recording with surface electrodes from the long (extrinsic) finger flexors is much more challenging (e.g., hard to avoid cross-task from other forearm muscles). Electrodes were also positioned on the extensor indicis muscle of the left and right forearm to measure extensor activity, with a ground electrode positioned on each upper forearm. The muscle was identified by having the participant disengage all finger muscles by relaxing the wrist in the air, and then extending and flexing the index finger, to ensure that the muscle was correctly isolated. This muscle was chosen as an index finger extensor (antagonist to the FDI). EMG data was fed into a CED amplifier and recorded for offline analysis (CED signal 1401 and 1902 devices). If the EMG signal became noisy (i.e., unintended activation of the muscles not related to the responses following presentation of the stimuli), the experimenter instructed the participant to relax their hands.

Stop-signal motor task. Psychopy (Peirce, 2009), a Python based software, was used for presentation of the visual stimuli for the stop-signal task. Several iterations of the presentation of the stimuli were piloted, with the final presentation involving the stimuli being presented on a black screen, with green ‘go’ stimuli and red ‘stop’ stimuli (Figure 1). Two different sets of buttons were used as the response key for the task, stiff buttons requiring greater force to depress the button and thus register a response, and compliant buttons requiring minimal force to register a response.

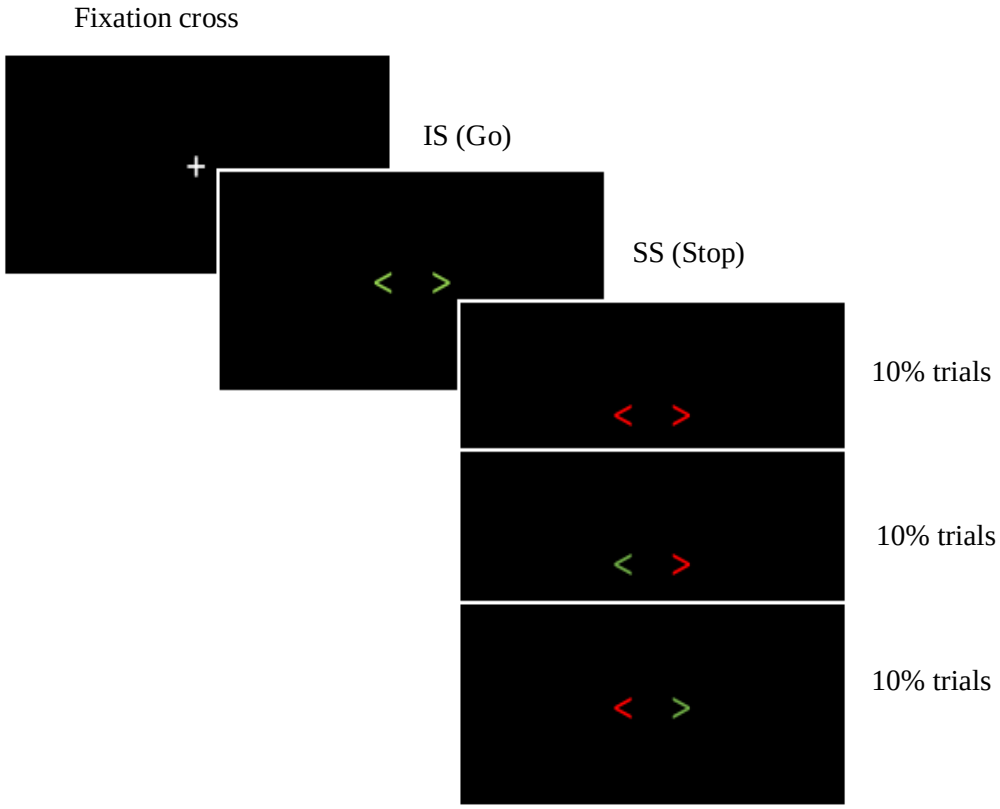

Figure 1. The presentation of the stop-signal task visual stimuli in the current study. A centrally located fixation cross was presented for between 500-700 ms. At the offset of the fixation cross, the imperative signal (IS) would then appear for 500ms, or on 30% of trials the stop-signal (SS) would appear SSD ms after presentation of the IS. The 30% of SS trials comprised of 10% of each stop type (bimanual stop, left stop, right stop).

Procedure:

Participants were seated at a desk approximately 80cm away from a display monitor with forearms resting comfortably on the desk and index fingers placed on the buttons which were positioned approximately shoulder width apart. An initial instruction page was shown to participants, as well as a verbal explanation of the task, which was consistent between participants. A fixation cross was presented for 500-700 ms (M=600 ms) at the start of each trial, the length of which was randomised between trials, in order to prevent participants from issuing delayed responses to the fixation cross (temporal prediction of the upcoming imperative signal) rather than responding to the imperative stimuli. Immediately following the fixation cross, two green arrows were displayed (the 'go' signal), indicating that the participant should respond bimanually as fast as possible by pressing both buttons simultaneously. Following a successful response, between 150 and 1500ms (as this was the minimum and maximum response permitted), the screen would display the RT. On 30% of trials, one or both of the green arrows turned red shortly after they were presented, indicating that the participant must try to cancel their response. Some trials assessed global inhibition by requiring both hands to be cancelled (both arrows turn red), and some trials assessed selective inhibition by requiring only one hand to be cancelled and the other to continue responding (either the left or the right arrow turns red). The likelihood of bimanual stop, left stop and right stop trials was equal (each 10% of total trials). The time period between the 'go' stimulus onset and the 'stop' stimulus is the stop-signal delay (SSD), and this time period changed iteratively between each trial such that each participant was able to successfully cancel their action approximately 50% of the time in each stop type (bimanual, left stop, right stop). At the start of each block of 120 trials, the SSD would be set to 130ms, and depending on whether the participant successfully stopped or not on the first stop-signal, the SSD would either increase by 50ms (if a successful stop), making it harder for them to stop next time, or

decrease by 50ms (if an unsuccessful stop), making it easier for them to stop next time. The SSD for each stop type was incremented independently to allow performance in the different stops to be compared. Ten separate randomised blocks of 120 trials were presented in a randomised order to each participant, and on five blocks the participant would use the compliant buttons, and on five blocks they would use the stiff buttons, with the order of the button type counterbalanced between participants. Before starting the five blocks with each button, a practice block of 30 trials with three of each type of stop (bimanual, left stop, right stop) was presented to introduce the task and indicate to the participant the degree of force that each button type required; practice blocks were not part of the analysis.

Data Analysis

To determine the frequency of occurrences of covert (partial) responses, EMG data was analysed on a trial-by-trial basis (see Figure 2 for example). Nine cursors were placed on each data frame, creating eight individual time windows of 100ms, one being the baseline EMG prior to any stimuli being presented, and seven 100ms brackets from 100 to 700ms post-imperative stimulus. The maximum rms (root mean square) EMG was then determined in each window. A partial response was deemed to have occurred in a correctly countermanded trial when the maximum rmsEMG burst across all time windows (in that trial) exceeded a certain percentage (25, 50 or 75%) of the maximum rmsEMG burst in the corresponding hand averaged across all correct bimanual Go (biGo) trials. The dependent variable to represent partial responses was determined at the proportion of correctly stopped trials in which a partial response was deemed to have occurred (calculated for each stop type separately). For bimanual stop trials, partial responses were calculated for both hands, while for selective stops, partial responses were only calculated for the stopping hand.

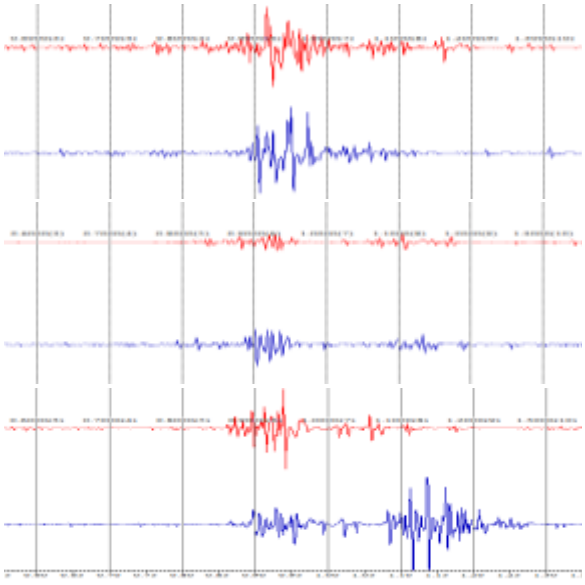

Figure 2. Example EMG data of three stop types (top to bottom): Successful bimanual go trial (equivalent to failed bimanual stop), successful bimanual stop (with partial response in both hands), successful left stop (with global partial response prior to right hand response). Note scale is the same for each sample. Red trace: Left FDI; Blue tract: Right FDI. (Extensor muscles not shown.)

The independent variables for partial response analysis were button type (stiff/compliant), stop type (global/selective), partial response threshold percentage (25/50/75) and (for the bimanual stops) hand used (left/right).

The behavioural dependent variables were stop signal RT (SSRT) (bimanual go RT – SSD) and cost of selective stop (selective stop RT – bimanual go RT).

Data was analysed in a series of repeated measures two- and three-way ANOVAs as well as a Student's T-test to determine button type differences between bimanual go RT. A 2 x 3 ANOVA was conducted on participant's mean stop-signal RT (SSRT), an indication of their stopping ability, to determine whether this varied between button type (compliant/stiff) and stop type (bimanual, left stop, right stop). A 2 x 2 ANOVA between button type (compliant, stiff) and selective stop types (left, right) was conducted to determine the cost of a selective stop (time difference between selective and global responding). A 2 x 3 ANOVA was conducted to determine whether participant's percentage of correct stops as a function of button type or stop type (bimanual, left, right). Finally, a 3 x 2 x 2 ANOVA between percentage threshold (25, 50, 75%), button type and hand used (left, right), was conducted to

determine how frequently partial responses occurred in the global stop conditions; and a 2 x 3 x 2 ANOVA between stop type (left stop, right stop), percentage threshold and button type was conducted to determine how frequently partial responses occurred in the selective stop conditions.

Any violations of the sphericity assumption ($\varepsilon < 0.7$) of a repeated measures ANOVA had Greenhouse-Geisser epsilon corrections applied. The level of significance for all analyses was set at p=.05; any main effects and interactions that were found to be significant were followed up with Bonferroni post-hoc pairwise comparisons. Cohen's *d* and partial-eta squared (η_p^2) values were provided as measures of effect size, with cut-offs of ≥0.2 small, ≥0.5 medium, ≥0.8 large for Cohen's *d*, and ≥0.01 small, ≥0.06 medium, and ≥0.14 large, for η_p^2. Means (*M)* and standard deviations (*SD*) are supplemented with estimates of confidence, with 95% confidence intervals provided in the format: CI [lower bound, upper bound]. In combination with effect sizes, 95% CIs can provide a more accurate representation of the results, and help to interpret the effect of the variables (Bakker & Wicherts, 2011).

Results

All participants executed the task well, and were able to complete all ten blocks with no participants dropping out.

Behavioural Results

Reaction time. A paired samples t-test revealed that correct biGo RT with the compliant button (M=456.52ms, SD=77.35ms) was significantly shorter than RT with the stiff button (M=512.64ms, SD=92.55ms), $t(24)=6.36$, $p<.001$, and this was associated with a medium effect size (d=.66).

As a manipulation check for the stop types, a 2 x 4 ANOVA (button type x trial type) was used to compare RT of failed stop trials (failed bimanual-stop, failed left-stop, failed right-stop) to RT in biGO trials, for the stiff and compliant button. This revealed a significant main effect of trial type, $F(3,72)= 73.59$, $p<.001$, $\eta_p^2=.75$, and button type, $F(1,24)= 34.19$, $p<.001$, $\eta_p^2=.59$, as well as a significant interaction between stop type and button type, $F(3,72)= 3.11$, $p=.032$, $\eta_p^2=.12$. Importantly, pairwise comparisons indicated that the effect of stop type indicated that the biGo RT (M=484.58ms, SD=82.40ms; CI [450.57ms, 518.59ms]), was significantly longer than the failed biStop (M=436.04ms, SD=74.25ms, CI [405.39ms, 466.69ms]), failed L-stop (M=438.24ms, SD=72.70ms, CI [408.24ms, 468.25ms]), and failed R-stop (M=435.94ms, SD=66.85ms, CI [408.35ms, 463.53ms]), (all comparisons $p<.001$), while none of the failed stops differed from one another (p=1.00). This is as expected, and indicates that participants were unable to stop their response when they responded quicker than average. The interaction was not followed up as it was not of theoretical interest to the current study.

Stop-signal reaction time. A 2 x 3 ANOVA revealed a significant main effect of button type, $F(1,24)=32.91$, $p<.001$, $\eta_p^2=.58$; SSRT was significantly longer for the stiff button (M=304.19ms, SD=38.45ms, CI [288.32ms, 320.06ms]) than for the compliant button (M=278.39ms, SD=28.78ms, CI [266.51ms, 290.26ms]). The main effect of stop type was not statistically significant, $F(2,48)=1.01$, $p=.370$, $\eta_p^2=.04$, indicating that the bimanual stop (M=291.40ms, SD=32.99ms, CI [277.78ms, 305.02ms]), left stop (M=289.38ms, SD=34.03ms, CI [275.33ms, 303.43ms]), and right stop (M=293.08ms, SD=31.67ms, CI [280.01ms, 306.15ms]), were not significantly different from one another. The two-way interaction was also not statistically significant, $F(2,48)=1.25$, $p=.295$, $\eta_p^2=.05$.

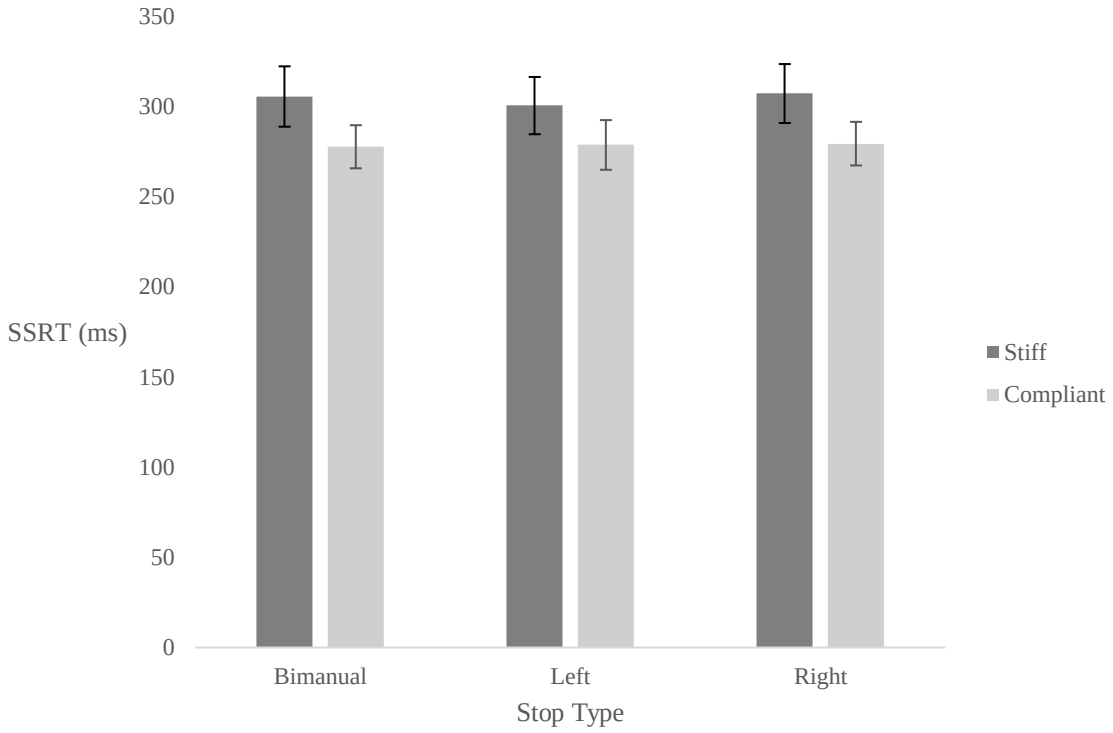

Figure 3. Stop-Signal RT: Stop type*button type interaction. Error bars denote 95% confidence interval range.

Selective stopping cost. A 2 x 2 ANOVA revealed a significant main effect of button type, $F(1,24)=31.06$, $p<.001$, $\eta_p^2=.56$; selective stopping cost was longer for the stiff buttons (M=152.60ms, SD=36.21ms, CI [137.66ms, 167.55ms]) than for the compliant buttons (M=127.48ms, SD=32.90ms, CI [113.90ms, 141.06ms]). The selective stopping cost for left stop (M=139.54ms, SD=29.28ms, CI [127.46ms, 151.63ms]) and right stop (M=140.54ms, SD=40.07ms, CI [124.00ms, 157.08ms]) trials did not differ significantly, $F(1,24)=0.04$, $p=.846$, $\eta p^2<.01$. The interaction effect was also not statistically significant, $F(1,24)=0.56$, $p=.463$, $\eta_p^2=.02$.

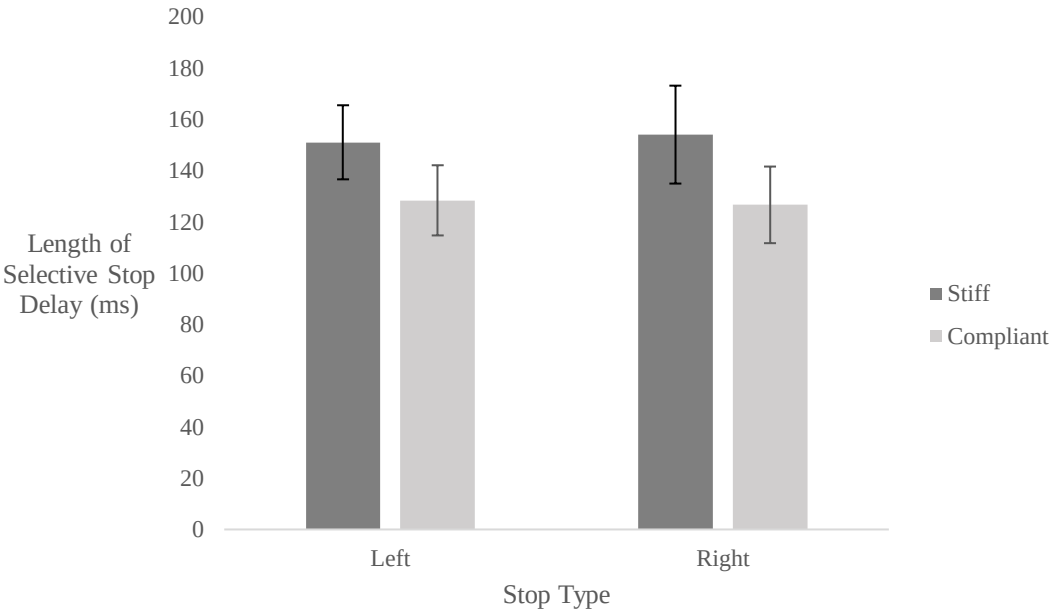

Figure 4. Cost of a selective stop: Delay in responding-limb RT in a selective stop compared to bimanual go RT. Error bars denote 95% confidence interval range.

Correct stop percentage. A 2 x 3 ANOVA revealed a significant main effect of button type, $F(1,24)=15.50$, $p=.001$, $\eta_p^2=.39$, with the stiff button ($M=63.04\%$, $SD=11.19\%$, CI [58.42%, 67.66%]) exhibiting a higher stopping rate than the compliant button ($M=58.60\%$, $SD=10.04\%$, CI [54.44%, 62.73%]). There was no significant main effect of stop type, $F(2,48)=.83$, $p=.441$, $\eta_p^2=.03$, indicating that the bimanual stops ($M=61.08\%$, $SD=10.06\%$, CI [56.93%, 65.23%]), left stops ($M=60.88\%$, $SD=10.42\%$, CI [56.58%, 65.18%]) and right stops ($M=60.48\%$, $SD=10.54\%$, CI [56.13%, 64.83%]) exhibited performance that did not differ significantly from each other. While there was a significant interaction between button type and stop type, $F(2,48)=3.90$, $p=.027$, $\eta_p^2=.14$, this was not theoretically relevant as stopping performance was not an outcome measure, but instead a check on the SSD staircase algorithm. Therefore, pairwise comparisons were not conducted.

Physiological Results

Global stop EMG analysis. A three-way ANOVA of frequency of partial responses in correctly inhibited bimanual (global) stop trials revealed a significant main effect of partial response threshold (25%: $M=23.36\%$, $SD=12.82\%$, CI [18.07%, 28.65%]; 50%: $M=11.64\%$, $SD=7.42\%$, CI [8.58%, 14.70%]; 75%; $M=4.36\%$, $SD=3.92\%$, CI [2.74%, 5.98%]), $F(1.11, 26.64) = 91.31$, $p<.001$, $\eta_p^2= .79$. The button type main effect was also statistically significant, $F(1,24)=37.38$, $p<.001$, $\eta_p^2= .61$, with the stiff buttons ($M=20.85\%$, $SD=11.36\%$, CI [16.16%, 25.53%]) yielding a greater proportion of correctly stopped global stop trials with partial responses than the compliant buttons ($M=5.39\%$, $SD=8.60\%$, CI [1.85%, 8.94%]). The proportion of trials in which partial responses were observed did not vary significantly between the left ($M=13.68\%$, $SD=8.48\%$, CI [10.18%, 17.18%]) and right ($M=12.56\%$, $SD=7.69\%$, CI [9.39%, 15.73%]) hands, $F(1, 24)=1.94$, $p=.177$, $\eta_p^2=.08$.

The two-way interaction between response threshold and button type was also statistically significant, $F(1.28, 30.75)=70.01$, $p<.001$, $\eta_p^2=.75$, indicating that the effect of button type varied as a function of response threshold (Figure 5). Post-hoc pairwise comparisons revealed that at all response thresholds, the proportion of trials in which partial responses were observed was higher for the stiff compared to the compliant button (Table 1). Furthermore, for the stiff button, partial responses were more frequent at the 25% threshold, compared to the 50% (difference: $M=17.74\%$, $SD=8.8\%$, CI [13.22%, 22.26%], $d=1.16$) and 75% (difference: $M=30.36\%$, $SD=14.4\%$, CI [22.96%, 37.77%], $d=2.23$) thresholds, and were more frequent at the 50% threshold than the 75% threshold (difference: $M=12.62\%$, $SD=7.05\%$, CI [8.98%, 16.26%], $d=1.43$) (all $p<.001$). For the compliant button, partial responses were also more frequent at the 25% threshold compared to the 50% (difference: $M=5.70\%$, $SD=6.15\%$, CI [2.54%, 8.86%], $d=0.54$) and 75% (difference: $M=7.64\%$, $SD=7.75\%$, CI [3.66%, 11.62%], $d=0.79$) thresholds (both $p<.001$), and were more frequent at the 50% threshold than the 75% threshold (difference: $M=1.94\%$, $SD=2.95\%$, CI [0.43%, 3.45%, $d=0.27$) ($p=.009$).

Table 1. Pairwise comparison of the significant interaction between button type and percentage threshold. Values denote differences in percentage of partial responses between stiff and compliant buttons at each threshold level.

Percentage threshold	*M* (*SD*)	95%*CI*	*p*	*d*
25%	27.04 (18.25)	19.50, 34.57	<.001	1.72
50%	15.00 (13.2)	9.55, 20.45	<.001	1.50
75%	4.32 (8.0)	1.02, 7.62	.013	0.77

There was also a statistically significant interaction between button type and hand, $F(1, 24)=4.71$, $p=.040$, $\eta_p^2=.16$, indicating that the effect of button type on the proportion of trials exhibiting partial responses varied as a function of hand used; however this effect was associated with a smaller effect size than the aforementioned response x button type interaction. Post-hoc pairwise comparisons revealed that the left hand and right hand did not produce significantly different proportions of partial responses for both the stiff button (difference: $M=2.04\%$, $SD=5.20\%$, CI [-0.11%, 4.19%], $p=.062$, $d=0.18$) and for the compliant button (difference: $M=0.20\%$, $SD=3.75\%$, CI [-1.35%, 1.75%], $p=.793$, $d=0.02$). Furthermore, for both the left (difference: $M=16.37\%$, $SD=13.15\%$, CI [10.95%, 21.80%] $d=1.53$) and right (difference: $M=14.53\%$, $SD=12.50\%$, CI [9.38%, 19.68%], $d=1.47$) hands, the stiff button yielded more partial responses than the compliant button (both $p<.001$).

The interaction between response threshold and hand used, $F(2, 48)=1.03$, $p=.366$, $\eta_p^2=.04$, as well as the three-way interaction between all variables, $F(2, 48)=0.33$, $p=.720$, $\eta_p^2=.01$, were both not statistically significant.

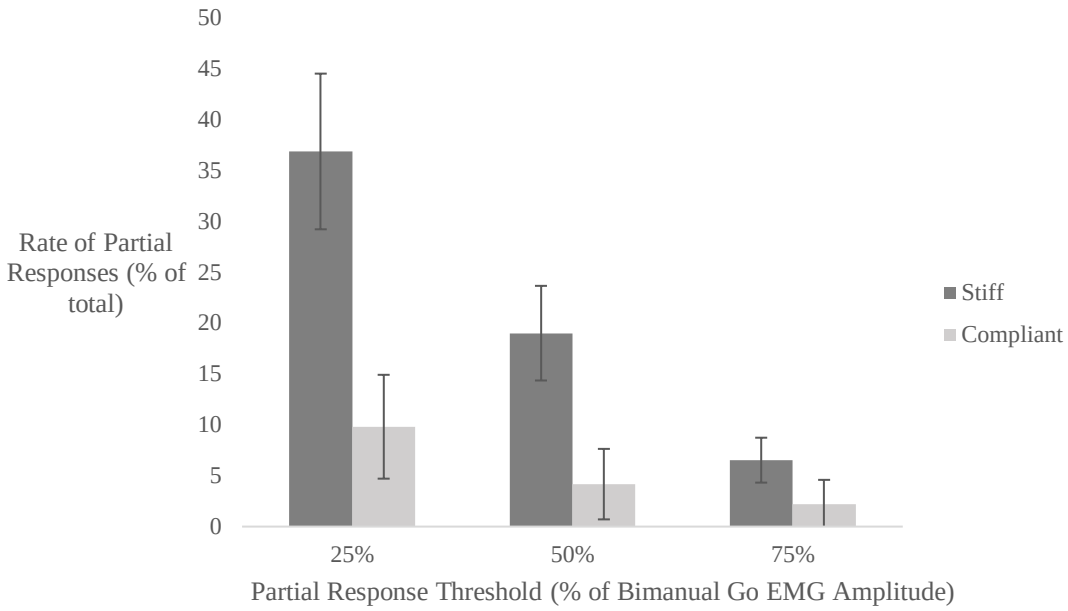

Figure 5. Rate of partial responses for bimanual stop conditions between stiff and compliant buttons: Interaction between button type and partial response threshold. Error bars represent 95% confidence intervals. Note data is averaged across the left and right hands.

Selective stop condition EMG analysis. A three way ANOVA revealed a significant main effect of partial response threshold (25%: M=30.82%, SD=14.58%, CI [24.80%, 36.84%]); 50%: M=8.55%, SD=11.06%, CI [3.99%, 13.11%]; 75%: M=5.82%, SD=4.02%, CI [4.16%, 7.48%]), $F(2,48)=67.35$, $p<.001$, $\eta_p^2=.74$. There was also a main effect of button type (compliant: M=20.31%, SD=10.84%, CI [15.84%, 24.79%]; stiff: M=9.81%, SD=6.31%, CI [7.21%, 12.42%]), revealing the stiff button yielded more partial responses than the compliant button, $F(1,24)=84.79$, $p<.001$, $\eta_p^2=.80$. There was no significant effect of stop type (left stop: M=15.47%, SD=9.66%, CI [11.49%, 19.46%]; right stop: M=14.65%, SD=8.46%, CI [11.16%, 18.15%]), $F(1,24)=0.34$, $p=.559$, $\eta_p^2=.01$.

There was a significant interaction between response threshold and button type (Figure 6), $F(2,48)=23.88$, $p<.001$, $\eta_p^2=.50$. Post-hoc comparisons revealed that the

proportion of trials in which partial responses were observed was higher for the stiff compared to the compliant buttons at each of the threshold levels (difference at 25% level: M=17.76%, SD=7.79%, CI [14.54%, 20.98%], d=1.18; difference at 50% level: M=6.78%, SD=7.78%, CI [3.57%, 9.99%], d=0.58; difference at 75% level: M=6.96%, SD=7.74%, CI [3.79%, 10.13%], d=1.25) (all p<.001). Furthermore, for the stiff button, partial responses were more frequent at the 25% threshold, compared to the 50% (difference: M=27.76%, SD=15.25%, CI [19.91%, 35.61%], d=1.75) and 75% (difference: M=30.40%, SD=12.46%, CI [23.99%, 36.81%], d=2.34) thresholds (both p<.001), but there was no significant difference between the 50 and 75% thresholds (difference: M=2.64%, SD=13.19%, CI [-4.15%, 9.43%], d=0.24, p=.980). For the compliant button, partial responses were more frequent at the 25% threshold compared to the 50% (difference: M=16.78%, SD=14.26%, CI [9.44%, 24.12%], d=1.57) and 75% (difference: M=19.60%, SD=13.20%, CI [12.80%, 26.40%], d=2.08) thresholds (both p<.001), and there was a significant difference in partial responses between the 50% and 75% thresholds (difference: M=2.82%, SD=4.74%, CI [0.38%, 5.26%], d=0.40, p=.020).

Interactions between stop type and button type, $F(1,24)=1.65$, p=.211, η_p^2=.06, and between stop type and response threshold, $F(2,48)=71.89$, p=.257, η_p^2=.06, were both non-significant. The three-way interaction between all variables was also non-significant, $F(2,48)=2.69$, p=.078, η_p^2=.10.

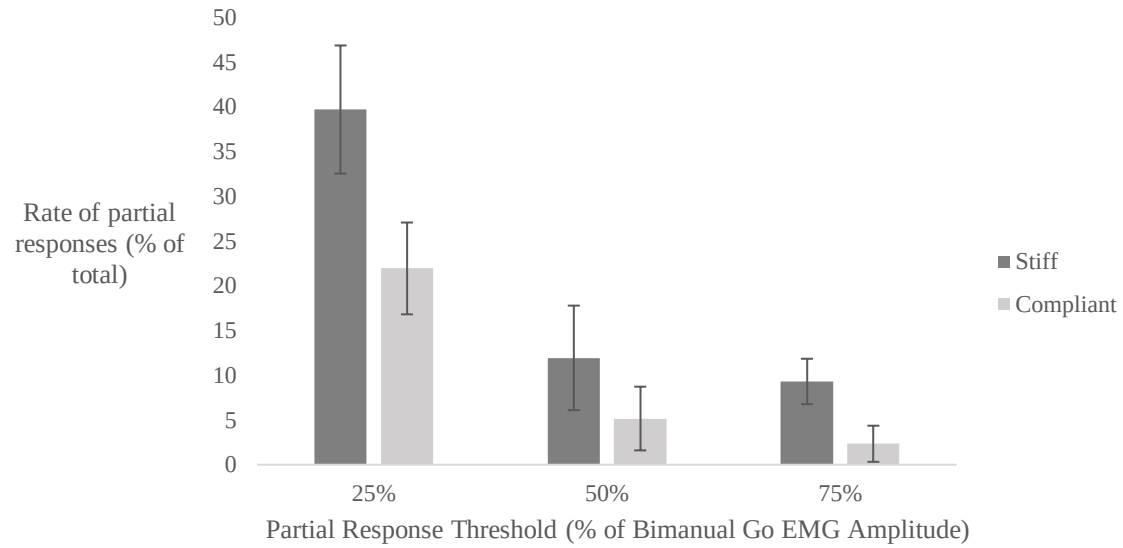

Figure 6. Rate of partial responses for selective stop conditions between stiff and compliant buttons: Interaction between button type and partial response threshold. Error bars represent 95% confidence intervals. Note data is averaged across left-stop and right-stop conditions.

Discussion

The current study used trial-by-trial analysis of muscle activity to provide a measure of covert (partial) responses during a modified stop-signal task. Together with standard behavioural indices of stopping performance, analysis of covert responses provided a window into the underlying mechanisms of global and selective inhibition. The use of partial responses to understand both selective and global stopping mechanisms represents a significant step forward in this technique. Another novel aspect of the project involved using two different button types for the behavioural task, allowing us to investigate how task constraints, i.e., manipulating the force required to register a response, can provide further insights into the models that assist in the understanding of inhibitory processes. The sample size permitted a reasonably powered study, such that effects were large and robust, indicating that the results are likely to represent true and repeatable findings.

Consistent with the hypotheses, the manipulation of the type of buttons had a significant effect on all dependent measures, and the results provide important evidence for and against specific inhibitory control models. Here the specific results are discussed in relation to these models, and then the broader implications, limitations and directions for future research will be considered.

The characteristics of the response buttons have substantial effects on stopping ability

A novel and key finding of the current research, and consistent with the hypothesis, is the effect that the stiff buttons had on both go and stop performance. The stiff button resulted in longer RTs, but importantly, it led to longer SSRT, which suggests that the stiff button elicited worse stopping performance. This is consistent the fact that there were also significantly greater rates of partial responses elicited by the stiff buttons than the compliant buttons, and this may be evidence that the stiff button led to worse inhibitory control, as some

researchers have suggested that evidence of partial responses indicates leakage of the stopping responses, and therefore imperfect stopping (McGarry & Franks, 1997). Therefore, both lines of evidence suggest that the stiff button led to worse inhibitory control. The results also have important implications for the assumptions of the horse race model of inhibition as this model suggests going and stopping are independent processes that race until they reach a point of no return (Logan & Cowan, 1984).

The presence of partial responses challenges the assumption of independent go and stop processes, as it suggests that the action is able to be countermanded, even after the muscle has been activated (Rochet et al., 2013). According to Servant and colleague's (2015) interpretation of the point of no return, evidence of partial responses indicate that following the activation of the motor activity, there is a period during which the action can still be prevented, and correction can be made. However, if the response had occurred, this would indicate that the evidence had accumulated during that time period until it reached a final criterion after which no correction can occur (Servant et al., 2015). This can explain the existence of partial responses, as it suggests that the partial response occurs prior to the final criterion, yet after the initial criterion signaling movement, and therefore the response can still be inhibited after the muscle activity begins, in that period between the two thresholds (Servant et al., 2015). Similarly, the current research provides evidence that supports McGarry and Frank's (1997) original research into EMG and partial responses, which found that response production can be inhibited both prior to, and following, muscle activation associated with the response (that is to be inhibited). This indicates that the point of no return occurs following motor activation, and also occurs later in the motor production process than initially thought by researchers who posited a horse race model with independent going and stopping processes (Logan & Cowan, 1984).

The current results also highlight that the mechanical characteristics of the response device (i.e., the force required to register a response on the stiff or compliant buttons) can significantly impact upon stopping ability. Here we observed that the stiff button led to longer SSRT, and also many more partial responses, evidence of imperfect stopping ability and potential leakage of the stopping process. These lines of evidence suggest worse inhibitory control when the stiff button was used. Accordingly, external factors such as the constraints of the task (which may include the button characteristics, but may also include other modifiable factors such as muscle used to respond, specific instructions about the task etc.) can interact with our indices of inhibitory function. This finding further challenges the notion of an internally generated point of no return, and instead indicates that external factors can alter whether or not a response is produced.

The method we used to detect partial responses revealed a substantially higher proportion of trials with partial responses than previous literature, where partial responses occurred in 15-20% of correctly stopped trials (Burle, Roger, Allain, Vidal, & Hasbroucq, 2008; Rochet et al., 2012; Servant et al., 2015), with tasks involving incongruent trials (flanker tasks) yielding slightly higher partial response rates (26%, Servant et al., 2015). However in this task, partial responses were detected in up to 40% of trials when using the stiff button (and conceivably much higher if we had imposed a lower threshold to detect a partial response, e.g., 10% of the rms EMG of a biGo trial). This indicates the technique utilised (as well as the task employed) provided a sensitive measure of partial responses, both due to EMG measurement, and also the stop-signal task and the button press manipulation. Accordingly, using this method of detecting partial responses could be beneficial in a number of situations, for example where partial response rates have been very low in previous research, for characterising changes of mind in perceptual choice tasks, or for detecting sub-threshold decisions in decision-making tasks.

Selective inhibition incurs a stopping cost, but is no more difficult than global stopping

Consistent with the hypothesis, there was a time cost associated with selective stopping of around 100ms, indicating that a unimanual movement involving selective inhibition required extra time to be executed, as compared to the standard bimanual response. This interference cost is consistent with the stopping cost found in research by Coxon et al. (2007); they suggested that this is reflective of a nonselective global braking that occurs upstream from the motor cortex, followed by a release of inhibition of the correctly responding limb. Similarly, this finding of an interference cost may be explained by MacDonald and colleagues (2017) activation threshold model, which suggests that a selective stop requires more sensory information than a global stop.

While there was a time cost associated with selective stopping, the current research found no difference in performance between global and selective inhibition (based on SSRT), indicating that selective stopping was, in this instance, no more difficult than global stopping. This is not consistent with the previous research, which suggested that global stopping is easier to engage in than selective (Coxon et al., 2007), and therefore this is an intriguing result. This may be because the selective stops (20% total) were more likely to occur than a global stop (10% total), so participants were primed for a selective stop more than they were for a global stop, however this assumes that participants figured out the likelihood of stopping for each stop type. Further research is required to investigate this finding to elucidate why selective stopping may have been no harder than global stopping. This research could change the likelihood of each stop type during the stop-signal task, or alternatively have participants complete blocks with only one stop type rather than mixed blocks with all stop types included, as was the case in the current study. This further research may find that a different inhibitory mechanism is employed when different stop types are

more likely, rather than the mechanism used when the chance of each stop type is the same, which may be a more generic strategy.

SSRT measure suggests that the stiff button did not lead to better inhibitory control

SSRT reflects an individual's inhibitory control ability, with shorter SSRT indicating better inhibitory control. In the current study, the stiff button produced a longer SSRT, which unexpectedly indicated worse inhibitory function. This may be due to a stronger force requirement on the stiff buttons, meaning M1 is required to issue a stronger, more forceful motor command to depress the button in the required biGo trials. It is therefore conceivable that more forceful commands lead to greater bimanual activity and so it is therefore more difficult to countermand both the selective and partial stops. In addition, these strong descending commands may have a rapid "turn-on" effect of EMG (at the onset of the muscle burst) to execute the button press. This effect may be more difficult to "turn-off" than the compliant button, with the compliant button requiring a less forceful and more gradual turn-on of motor units to generate the button press, explaining why the stiff button elicited more partial responses than the compliant button. It would therefore be important that future research investigate these suggestions and ascertain why the buttons give different indices of stopping ability.

Antagonist Muscle Exploratory Component

As an exploratory component to the research, we measured the extensor indicis, the primary agonist to index finger flexion, in order to investigate whether active engagement of the extensor was involved in cancellation of movement (i.e., whether stopping simply involved cancellation of a flexion response or whether active extension, or withdrawal, was observable). Initial observations of the data indicated that following each flexor movement,

there was a lesser extensor movement, regardless of trial type. Theorising that this may be an active mechanism that turns on in anticipation that a stop signal will occur, we ran five participants through two blocks of the same task but without any stop signals. We hypothesised that if the extensor muscle did engage as a mechanism for preventing movement should the stop-signal appear, this activity would not be present in this follow-up set of data, as no stops were present. However, once again the extensor activity was present, suggesting that the muscle is not involved in inhibition directly, but instead is part of the go response (potentially as part of an agonist-antagonist biphasic burst, where the antagonist helps to decelerate the initial acceleration as the force required is met and the button is depressed). Moreover, while the buttons recoil to the initial position (and thus no extensor activity is required to release the button) some active extension may be involved. However, the timing of the extensor burst we see (close to the flexor burst) suggest the former description is most likely. More thorough analysis of extensor bursts, beyond the scope of the current thesis, would be required to reveal the extent to which extensor activation may be involved in active cancellation of actions.

Limitations and Future Research

The rate of successful stopping data revealed that the SSD algorithm did not work as accurately as we had expected, and this was a limitation of the design of the algorithm. At the start of each block of the stop-signal task, the SSD returned to baseline (130ms, based on the initial piloting and existing research). Therefore, stopping in the first part of each block was easier than it should have been (130ms < the average SSD), and so the average stopping ability of each participant was increased, and overall the stopping success across all participants was around 60%, instead of the 50% that the algorithm was set to. To investigate whether this affected the data, we removed the first half of each block and re-ran the analysis

to determine if this reduced the stopping success. This lowered the average stopping success to around 57%, indicating that it did not hugely affect the data, and instead suggested that stopping performance being > 50% could be attributed to a small number of participants with particularly 'good' stopping performance (high %). These participants appeared to have wavered from task instructions in some instances, and slowed their Go responses during the task to try to make it easier for themselves to respond successfully to the stop-signal, and therefore their individual stopping success rates were around 65-70%. This effect does not significantly affect the data, and we do not believe that this has contributed to any other findings or discussion thereof, it would only have acted as a manipulation check. Re-running all analyses with particular participants (those with slow, or very variable go RT) filtered out would confirm the robustness of the currently reported finding for all of our behavioural and EMG measures.

Another potential limitation of the method used to analyse partial responses was using eight, time-locked windows. If a response occurred across two brackets, that is a response with a 350ms RT would be partly captured in the 3-400ms window and partly in the 4-500ms window, this would *underestimate* the magnitude of the partial response, as only part of it is taken into account. While our method was conservative, it was still sensitive enough to detect a very high percentage of partial responses, adding value to the current literature. That said, future research should aim to using a moving time window in order to further increase the sensitivity of partial response detection.

A limitation of EMG analysis is that it is such a sensitive measure, if the participant is unable to relax their muscles, the critical responses may get lost in the background noise. To combat this issue, the experimenter watched each EMG frame on the computer monitor as it happened, and whenever the signal became noisy would ask the participant to relax. However, this still meant that there was noise present at some times during the experiment,

and therefore some partial responses may not be detected. This indicates however that even with these issues that are largely unpreventable, the results showed a large number of partial responses and therefore may even be an underestimation of this rate.

Potential fatigue effects may have been present as the task was long—ten blocks of 120 trials meant that the total time spent doing the task, not including breaks, was more than an hour. However, this issue was judged as less important than obtaining enough trials to analyse the data successfully, and to permit computational modelling of the data (beyond the scope of the thesis). As we could only analyse stop trials, and these only appeared on thirty percent of trials (10% for each stop type), and of these the participant was expected to stop only fifty percent of the time, the pool of trials that were available for analysis was small. Taking into account these factors, we expected to have for each participant approximately thirty correct stop trials for each stop type (bimanual stop, left stop, right stop) per button. Unfortunately this is the nature of the task, but with breaks offered to participants between each block, we do not believe that this affected the data significantly. Fortunately, most participants performed well, concentrating and trying as best they could for the entire session. Overall, we did not see any block-by-block detriments in performance that were attributable to fatigue. Any fatigue effects, however, between the first and second half of the experiment, were mitigated by counterbalancing the buttons used (stiff/compliant in the first/second half) across participants.

Despite these limitations, the task was successful in detecting partial responses to a high degree of sensitivity, and it is therefore recommended that future research use this method to further investigate the mechanisms of inhibitory control. It is hoped that follow-up research be conducted investigating an older cohort in order to compare inhibitory processes across the lifespan and how they change with healthy ageing. As no difference was found between selective and global stopping it would be interesting to determine whether this

changes for healthy older adults, as it would be expected that the cohort would perform worse on selective stopping trials (Coxon et al., 2016).

Conclusion

The current study investigated the mechanisms and models that attempt to explain inhibitory control by using trial-by-trial EMG analysis to measure covert muscle activity as an indicator of inhibitory function. By using a unique manipulation of the stop-signal task, adding a stiffer set of buttons in addition to a compliant set, we aimed to investigate how inhibitory function would change based on greater force requirements to register a response. The results indicated that using a stiff button led to more partial responses and changes to inhibitory control, suggesting that the point of no return proposed in earlier research must occur later than previously thought, as muscle activity occurs prior to the response being countermanded.

The novel use of a button manipulation in conjunction with the stop-signal task and EMG analysis was successful in that more partial responses were detected than in previous research, and the method appears to be a sensitive measure of covert inhibitory control. Research into the mechanisms of inhibitory control is important as it may have utility in diagnosing and treating conditions such as ADHD, OCD and Tourette's Syndrome, all of which are associated with deficits in inhibitory control. The current study provides a well powered young cohort sample, against which future research into an older age group can be compared against, in order to also understand how inhibitory control changes across the lifespan.

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Appendix A

Ethics Approval Letter

From: Katherine Shaw (katherine.shaw@utas.edu.au)

To: Mark Hinder (mark.hinder@utas.edu.au)

CC: Jeffery Summers, Hakuei Fujiyama, Tino Stoeckel, Rohan Puri, Sara Forni Zervoudaki, Sarah Kemp, Abbey Lack, Anna Read, Paola Reissig, Angus Reynolds, Sara Waitzer

Subject: Ethics Amendment Approval: H0012358 Brain connectivity during movement planning and execution in young and older adults

Dear Dr Hinder

Ethics Ref: H0012358
Title: Brain connectivity during movement planning and execution in young and older adults

This email is to confirm that the following amendment was approved by the Chair of the Tasmania Social Sciences Human Research Ethics Committee on 28/4/2017:

- Addition of Honours students Abbey Lack and Anna Read.
- Revised Information Sheet and Information Sheet for behavioural testing.

All committees operating under the Human Research Ethics Committee (Tasmania) Network are registered and required to comply with the National Statement on Ethical Conduct in Human Research (NHMRC 2007, updated May 2015).

This email constitutes official approval. If your circumstances require a formal letter of amendment approval, please let us know.

Should you have any queries please do not hesitate to contact me.

Kind regards
Katherine

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CRICOS 00586B

Appendix B

Handedness Inventory and Colour-Blindness Screening Forms

HANDEDNESS INVENTORY

For each of the activities below, please tell us:

1. Which hand do you prefer for that activity?
2. Do you *ever* use the other hand for the activity?

	Preferred hand?		Ever use other hand?	
Writing	L	R	Y	N
Drawing	L	R	Y	N
Throwing	L	R	Y	N
Using scissors	L	R	Y	N
Using a toothbrush	L	R	Y	N
Using a knife (without fork)	L	R	Y	N
Using a spoon	L	R	Y	N
Using a broom (upper hand)	L	R	Y	N
Striking a match	L	R	Y	N
Opening a box (lid)	L	R	Y	N

Do you ever confuse left and right? ……....

How many people in your immediate family are left handed? ……

COLOUR-BLIND SCREENING

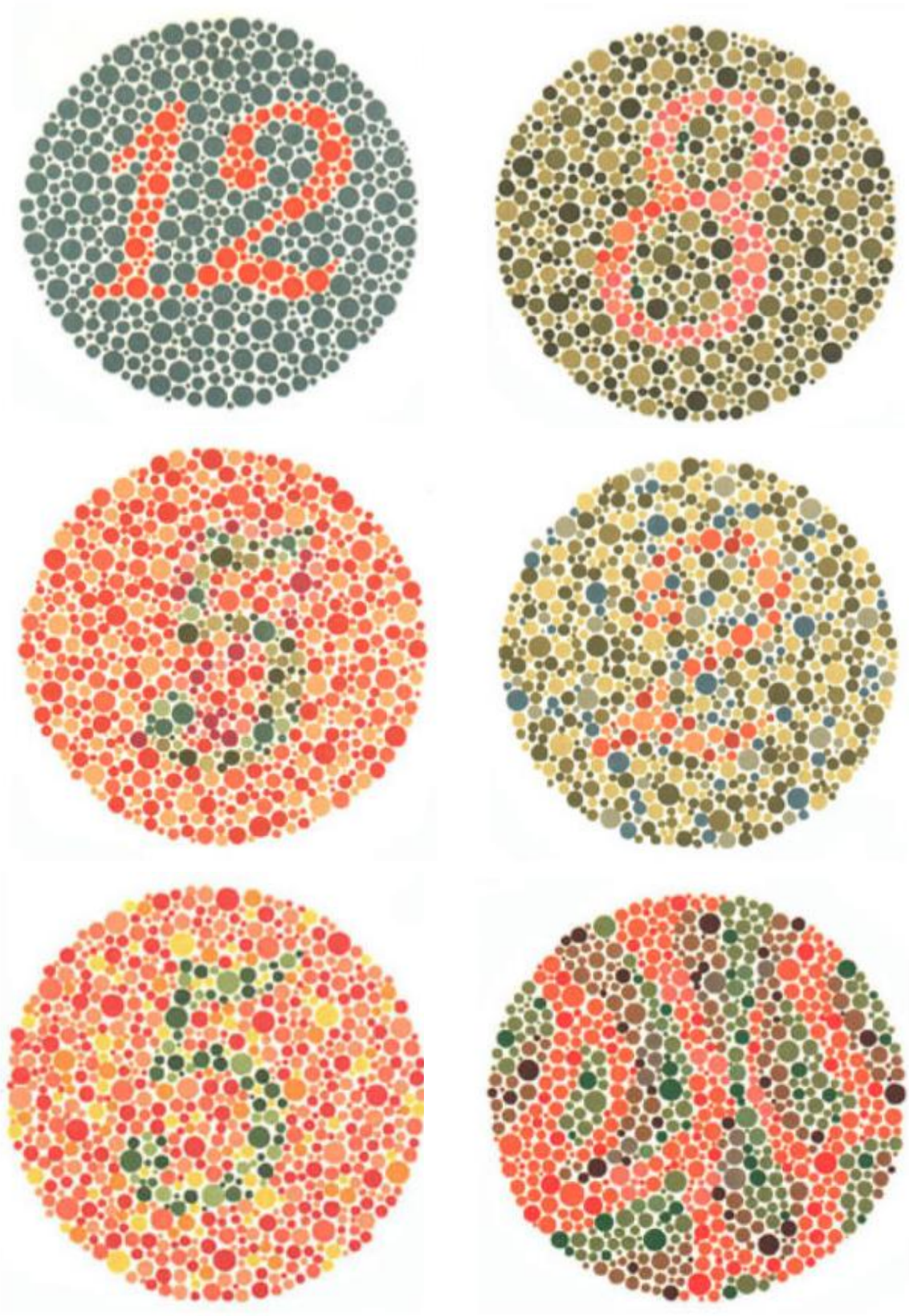
Please write your responses for the six images below (write the number that you see, or if you don't see a number, write 'no number')

Image 1:
Image 2:
Image 3:
Image 4:
Image 5:
Image 6:

THANK YOU FOR YOUR PARTICIPATION!

Appendix C

Colour Blindness Test Plates (Ishihara, 1972)



Appendix D

Information Sheet

INFORMATION SHEET – Behavioural testing

Brain connectivity during movement planning and execution in young and older adults

Chief Investigator: Dr Mark Hinder
Co-Investigators: Prof. Jeffery Summers, Dr Hakuei Fujiyama,
Student Investigators: Ms Paola Reissig, Mr Angus Reynolds, Ms Anna Read

Background and Benefit
You are invited to voluntarily participate in a research project examining the role of particular brain areas during the preparation and execution of voluntary movements. The aim of this research is to improve our understanding of how healthy ageing affects how different brain areas are utilised during movement. The research will aim to improve interventions/strategies to enhance or maintain motor function in older age. This research is funded by a grant from the Australian Research Council.

The particular study that you are undertaking today involves no brain stimulation methods and is solely a behavioural investigation, which may in future be used in conjunction with brain stimulation techniques. The experiment will be conducted in the Human Motor Control Laboratory in the Psychology Research Centre at the University of Tasmania. You may be asked to participate in multiple sessions. If this is the case the investigator will inform you before you begin of the number of sessions involved. A single session will last approximately two hours (it may be much shorter) and multiple sessions would be separated by at least 48 hours. Every effort will be made to schedule multiple sessions at mutually convenient times.

Study procedures
The following procedures will be used in this research: (a) voluntary movements of the hands/arms/legs.
b) passive recording of muscle activity (EMG) may occur in some experiments.

(a) Voluntary movements: You will be asked to perform a certain type of voluntary movement tasks using your hands and arms and legs. Examples include rapid finger movements or tapping, force control tasks, pushing buttons is response to visual or auditory signals and coordination of both arms or hands (e.g. tapping both index fingers, flexing-extending your wrist). These tasks are not physically demanding, but they may be performed for up to one hour which may cause some minor muscle fatigue. To minimise this, frequent rest periods will be provided throughout the session. The experimenter will explain exactly what movements you are required to perform before you begin the session.

(b) EMG: EMG is a technique to record the electrical activity of muscles during your movements – see (a). At the beginning of the experiment, small, self-adhesive recording electrodes will be affixed to the skin over the muscle of interest. Wires will be connected to the electrodes to allow the muscle activity to be recorded by a computer. To ensure the best possible recording, the skin will be prepared by scrubbing it with a mildly abrasive paste and then cleaning it with an alcohol wipe. If there is excessive hair on the skin (e.g., forearm muscles) a small area may be shaved using a disposable razor. This procedure may produce

some minor irritation of the skin (e.g., redness). The adhesives used on the electrodes are hypoallergenic.

Inclusion and Exclusion criteria
Individuals (male and female) between the ages of 18 and 80 years of age are invited to participate in this research. Interested volunteers should have normal or corrected-to-normal vision, and have no known neuromuscular or neurological disorders, or recent injuries of the hands or arms.

Risks and Discomforts
There are extremely minimal risks associated with the procedures used in this study. You may experience some minor muscle fatigue as a result of performing voluntary movements. If your muscles become uncomfortable as a result of the movements, please inform the experimenter. The passive electrodes that record muscle activity may cause some mild skin irritation and redness. In generally, if at any time you feel uncomfortable for any reason, please inform the experimenter and the procedures can immediately be stopped.

Payment
I understand that I will receive course credit for the total time that I am involved in the study, or will be eligible for a voucher to compensate me for time/travel costs.

Confidentiality and Anonymity
Your individual experimental data will be coded alpha-numerically and stored on a secure computer server that will be available only to the investigators via a password system. All future use of your data will be by the alpha-numeric code only to ensure anonymity. Your data will be retained securely at the University of Tasmania for at least five years. When it is no longer required by law, your data will be destroyed by the deletion of electronic files and shredding of documents.

Voluntary participation
Participation in the study is completely voluntary. If you agree to participate, you are free to withdraw from the study at any time without prejudice. If participation is for course-credit and you withdraw, you will receive credit for the time you have participated, up to a maximum of 2 hours. Otherwise, you will receive $5 for each half-hour of participation, up to a maximum of $20. If you withdraw from the study, any data that you have supplied can be identified through the alpha-numeric coding system and withdrawn from the study if you wish. You will be asked to sign an informed consent form to evidence your consent to participate in the study. Consent forms will be locked in a filing cabinet in the Human Motor Control Laboratory at the University of Tasmania and kept separately from your data.

Contact persons: If you wish to obtain more information, please contact one of the following researchers:
Dr. Mark Hinder (6226 2945 or Mark.Hinder@utas.edu.au)
Prof. Jeff Summers (6226 2884 or Jeff.Summers@utas.edu.au)

This study has been approved by the Tasmanian Social Sciences Human Research Ethics Committee. If you have concerns or complaints about the conduct of this study, please contact the Executive Officer of the HREC (Tasmania) Network on (03) 6226 7479 or email human.ethics@utas.edu.au. The Executive Officer is the person nominated to receive complaints from research participants. Please quote ethics reference number H12358. You will be provided with a copy of this information sheet and a statement of informed consent to keep. When finalised, results of the study will be posted on the University of Tasmania website, http://www.scieng.utas.edu.au/psychol/index.asp. It can be expected that results of individual studies will be available within a year of data collection.

Appendix E

Consent Form

School of Psychology

Informed Consent Form – Behavioural Testing

1. I have read and understood the Information Sheet for this study.

2. I understand that this experimental session will last no more than 2 ½ hours and that I may have been asked to undertake multiple sessions.

3. I understand that I will receive course credit for the total time that I am involved in the study, or will be eligible for a voucher to compensate me for time/travel costs.

4. I understand that all research data will be securely stored on the University of Tasmania premises for a period of 5 years. Electronic data will be stored on a password protected computer. All data will be destroyed at the end of 5 years.

5. Any questions that I have asked have been answered to my satisfaction.

6. I agree that research data gathered for the study may be published provided that I cannot be identified as a subject.

7. I agree to participate in this investigation and understand that I may withdraw at any time without any effect. Following completion of the experiment, please contact a researcher if you wish to have your data withdrawn from the study for any reason. Data can be withdrawn at any time until submission of the manuscripts for publication (~ 6-12 months following completion of data collection).

Name of Participant: _____

Signature of Participant: _____Date:_____

I have explained this project and the implications of participation in it to this participant, and I believe that the consent is informed and that he/she understands the implications of participation.

Name of Investigator: _____

Signature of Investigator: _____Date:_____

Appendix F

SPSS Output

Reaction Time

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	W_BIGO_RT	512.6400	25	92.55308	18.51062
	B_BIGO_RT	456.5200	25	77.35046	15.47009

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	W_BIGO_RT - B_BIGO_RT	56.12000	44.14023	8.82805	37.89981	74.34019	6.357	24	.000

Stop Type Manipulation Check

Descriptive Statistics

	Mean	Std. Deviation	N
BiGo_Correct_White	512.6400	92.55308	25
BiGo_Correct_Black	456.5200	77.35046	25
BiGo_Failed_White	461.0800	80.41244	25
BiGo_Failed_Black	411.0000	73.40640	25
LStop_Failed_White	464.1200	81.51601	25
LStop_Failed_Black	412.3600	72.36705	25
RStop_Failed_White	455.1200	68.99476	25
RStop_Failed_Black	416.7600	72.63280	25

Mauchly's Test of Sphericity[a]

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
StopType	.561	13.137	5	.022	.733	.810	.333
ButtonType	1.000	.000	0	.	1.000	1.000	1.000
StopType * ButtonType	.505	15.542	5	.008	.710	.781	.333

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
StopType	Sphericity Assumed	85993.960	3	28664.653	73.593	.000	.754
	Greenhouse-Geisser	85993.960	2.200	39084.122	73.593	.000	.754
	Huynh-Feldt	85993.960	2.431	35366.936	73.593	.000	.754
	Lower-bound	85993.960	1.000	85993.960	73.593	.000	.754
Error(StopType)	Sphericity Assumed	28044.040	72	389.501			
	Greenhouse-Geisser	28044.040	52.805	531.082			
	Huynh-Feldt	28044.040	58.355	480.572			
	Lower-bound	28044.040	24.000	1168.502			
ButtonType	Sphericity Assumed	120442.320	1	120442.320	34.187	.000	.588
	Greenhouse-Geisser	120442.320	1.000	120442.320	34.187	.000	.588
	Huynh-Feldt	120442.320	1.000	120442.320	34.187	.000	.588
	Lower-bound	120442.320	1.000	120442.320	34.187	.000	.588
Error(ButtonType)	Sphericity Assumed	84552.680	24	3523.028			
	Greenhouse-Geisser	84552.680	24.000	3523.028			
	Huynh-Feldt	84552.680	24.000	3523.028			
	Lower-bound	84552.680	24.000	3523.028			
StopType * ButtonType	Sphericity Assumed	2158.280	3	719.427	3.110	.032	.115
	Greenhouse-Geisser	2158.280	2.130	1013.228	3.110	.050	.115
	Huynh-Feldt	2158.280	2.344	920.956	3.110	.045	.115
	Lower-bound	2158.280	1.000	2158.280	3.110	.091	.115
Error(StopType*ButtonType)	Sphericity Assumed	16655.720	72	231.329			
	Greenhouse-Geisser	16655.720	51.122	325.800			
	Huynh-Feldt	16655.720	56.245	296.131			
	Lower-bound	16655.720	24.000	693.988			

Significant main effect of stop type

Estimates

StopType	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	484.580	16.477	450.573	518.587
2	436.040	14.851	405.389	466.691
3	438.240	14.538	408.235	468.245
4	435.940	13.367	408.352	463.528

Pairwise Comparisons

(I) StopType	(J) StopType	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	48.540*	4.565	.000	35.417	61.663
	3	46.340*	4.106	.000	34.534	58.146
	4	48.640*	5.037	.000	34.158	63.122
2	1	-48.540*	4.565	.000	-61.663	-35.417
	3	-2.200	3.560	1.000	-12.437	8.037
	4	.100	2.925	1.000	-8.309	8.509
3	1	-46.340*	4.106	.000	-58.146	-34.534
	2	2.200	3.560	1.000	-8.037	12.437
	4	2.300	3.030	1.000	-6.413	11.013
4	1	-48.640*	5.037	.000	-63.122	-34.158
	2	-.100	2.925	1.000	-8.509	8.309
	3	-2.300	3.030	1.000	-11.013	6.413

Significant main effect of button type

Estimates

Measure: MEASURE_1

ButtonType	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	473.240	15.971	440.277	506.203
2	424.160	14.474	394.287	454.033

Pairwise Comparisons

Measure: MEASURE_1

(I) ButtonType	(J) ButtonType	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	49.080*	8.394	.000	31.755	66.405
2	1	-49.080*	8.394	.000	-66.405	-31.755

Global Stop EMG Data

Descriptive Statistics

	Mean	Std. Deviation	N
p25_W_L	37.52	18.326	25
p25_W_R	36.24	19.810	25
p25_B_L	9.80	14.646	25
p25_B_R	9.88	11.519	25
p50_W_L	20.92	13.497	25
p50_W_R	17.36	10.049	25
p50_B_L	4.52	9.377	25
p50_B_R	3.76	7.595	25
p75_W_L	7.16	5.528	25
p75_W_R	5.88	5.819	25
p75_B_L	2.16	5.713	25
p75_B_R	2.24	6.050	25

Mauchly's Test of Sphericity[a]

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
threshold	.198	37.238	2	.000	.555	.562	.500
button	1.000	.000	0	.	1.000	1.000	1.000
hand	1.000	.000	0	.	1.000	1.000	1.000
threshold * button	.439	18.935	2	.000	.641	.661	.500
threshold * hand	.746	6.739	2	.034	.797	.845	.500
button * hand	1.000	.000	0	.	1.000	1.000	1.000
threshold * button * hand	.671	9.171	2	.010	.753	.792	.500

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
threshold	Sphericity Assumed	18378.560	2	9189.280	91.311	.000	.792
	Greenhouse-Geisser	18378.560	1.110	16558.264	91.311	.000	.792
	Huynh-Feldt	18378.560	1.125	16338.405	91.311	.000	.792
	Lower-bound	18378.560	1.000	18378.560	91.311	.000	.792
Error(threshold)	Sphericity Assumed	4830.607	48	100.638			
	Greenhouse-Geisser	4830.607	26.638	181.340			
	Huynh-Feldt	4830.607	26.997	178.932			
	Lower-bound	4830.607	24.000	201.275			
button	Sphericity Assumed	17910.413	1	17910.413	37.381	.000	.609
	Greenhouse-Geisser	17910.413	1.000	17910.413	37.381	.000	.609
	Huynh-Feldt	17910.413	1.000	17910.413	37.381	.000	.609
	Lower-bound	17910.413	1.000	17910.413	37.381	.000	.609
Error(button)	Sphericity Assumed	11499.253	24	479.136			
	Greenhouse-Geisser	11499.253	24.000	479.136			
	Huynh-Feldt	11499.253	24.000	479.136			
	Lower-bound	11499.253	24.000	479.136			
hand	Sphericity Assumed	94.080	1	94.080	1.939	.177	.075

	Greenhouse-Geisser	94.080	1.000	94.080	1.939	.177	.075
	Huynh-Feldt	94.080	1.000	94.080	1.939	.177	.075
	Lower-bound	94.080	1.000	94.080	1.939	.177	.075
Error(hand)	Sphericity Assumed	1164.587	24	48.524			
	Greenhouse-Geisser	1164.587	24.000	48.524			
	Huynh-Feldt	1164.587	24.000	48.524			
	Lower-bound	1164.587	24.000	48.524			
threshold * button	Sphericity Assumed	6460.187	2	3230.093	70.009	.000	.745
	Greenhouse-Geisser	6460.187	1.281	5042.209	70.009	.000	.745
	Huynh-Feldt	6460.187	1.322	4887.276	70.009	.000	.745
	Lower-bound	6460.187	1.000	6460.187	70.009	.000	.745
Error(threshold*button)	Sphericity Assumed	2214.647	48	46.138			
	Greenhouse-Geisser	2214.647	30.749	72.023			
	Huynh-Feldt	2214.647	31.724	69.810			
	Lower-bound	2214.647	24.000	92.277			
threshold * hand	Sphericity Assumed	40.560	2	20.280	1.027	.366	.041
	Greenhouse-Geisser	40.560	1.595	25.431	1.027	.353	.041
	Huynh-Feldt	40.560	1.690	23.995	1.027	.356	.041
	Lower-bound	40.560	1.000	40.560	1.027	.321	.041
Error(threshold*hand)	Sphericity Assumed	948.273	48	19.756			
	Greenhouse-Geisser	948.273	38.278	24.773			
	Huynh-Feldt	948.273	40.569	23.374			
	Lower-bound	948.273	24.000	39.511			
button * hand	Sphericity Assumed	63.480	1	63.480	4.709	.040	.164
	Greenhouse-Geisser	63.480	1.000	63.480	4.709	.040	.164
	Huynh-Feldt	63.480	1.000	63.480	4.709	.040	.164
	Lower-bound	63.480	1.000	63.480	4.709	.040	.164
Error(button*hand)	Sphericity Assumed	323.520	24	13.480			
	Greenhouse-Geisser	323.520	24.000	13.480			
	Huynh-Feldt	323.520	24.000	13.480			
	Lower-bound	323.520	24.000	13.480			
threshold * button * hand	Sphericity Assumed	8.640	2	4.320	.331	.720	.014
	Greenhouse-Geisser	8.640	1.505	5.741	.331	.659	.014
	Huynh-Feldt	8.640	1.584	5.455	.331	.670	.014
	Lower-bound	8.640	1.000	8.640	.331	.570	.014
Error(threshold*button*hand)	Sphericity Assumed	625.860	48	13.039			
	Greenhouse-Geisser	625.860	36.122	17.326			
	Huynh-Feldt	625.860	38.011	16.465			
	Lower-bound	625.860	24.000	26.078			

Significant main effect of threshold

Estimates

threshold	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	23.360	2.564	18.067	28.653
2	11.640	1.483	8.579	14.701
3	4.360	.783	2.744	5.976

Pairwise Comparisons

(I) threshold	(J) threshold	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	11.720*	1.274	.000	8.440	15.000
	3	19.000*	1.932	.000	14.029	23.971
2	1	-11.720*	1.274	.000	-15.000	-8.440
	3	7.280*	.826	.000	5.153	9.407
3	1	-19.000*	1.932	.000	-23.971	-14.029
	2	-7.280*	.826	.000	-9.407	-5.153

Significant main effect of button type

Estimates

button	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	20.847	2.271	16.159	25.534
2	5.393	1.719	1.846	8.941

Pairwise Comparisons

(I) button	(J) button	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	15.453*	2.528	.000	10.237	20.670
2	1	-15.453*	2.528	.000	-20.670	-10.237

*Significant threshold * button type interaction*

Estimates

threshold	button	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	36.880	3.704	29.236	44.524
	2	9.840	2.470	4.742	14.938
2	1	19.140	2.252	14.493	23.787
	2	4.140	1.677	.679	7.601
3	1	6.520	1.069	4.314	8.726
	2	2.200	1.168	-.210	4.610

Pairwise Comparisons

threshold	(I) button	(J) button	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
1	1	2	27.040*	3.651	.000	19.504	34.576
	2	1	-27.040*	3.651	.000	-34.576	-19.504
2	1	2	15.000*	2.639	.000	9.553	20.447
	2	1	-15.000*	2.639	.000	-20.447	-9.553
3	1	2	4.320*	1.600	.013	1.017	7.623
	2	1	-4.320*	1.600	.013	-7.623	-1.017

Pairwise Comparisons

button	(I) threshold	(J) threshold	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
1	1	2	17.740*	1.758	.000	13.216	22.264
		3	30.360*	2.877	.000	22.955	37.765
	2	1	-17.740*	1.758	.000	-22.264	-13.216
		3	12.620*	1.414	.000	8.981	16.259
	3	1	-30.360*	2.877	.000	-37.765	-22.955
		2	-12.620*	1.414	.000	-16.259	-8.981
2	1	2	5.700*	1.226	.000	2.544	8.856
		3	7.640*	1.548	.000	3.657	11.623
	2	1	-5.700*	1.226	.000	-8.856	-2.544
		3	1.940*	.588	.009	.426	3.454
	3	1	-7.640*	1.548	.000	-11.623	-3.657
		2	-1.940*	.588	.009	-3.454	-.426

*Significant hand * button type interaction*

Estimates

threshold	button	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1	1	36.880	3.704	29.236	44.524
	2	9.840	2.470	4.742	14.938
2	1	19.140	2.252	14.493	23.787
	2	4.140	1.677	.679	7.601
3	1	6.520	1.069	4.314	8.726
	2	2.200	1.168	-.210	4.610

Pairwise Comparisons

threshold	(I) button	(J) button	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
1	1	2	27.040*	3.651	.000	19.504	34.576
	2	1	-27.040*	3.651	.000	-34.576	-19.504
2	1	2	15.000*	2.639	.000	9.553	20.447
	2	1	-15.000*	2.639	.000	-20.447	-9.553
3	1	2	4.320*	1.600	.013	1.017	7.623
	2	1	-4.320*	1.600	.013	-7.623	-1.017

Pairwise Comparisons

hand	(I) button	(J) button	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
1	1	2	16.373*	2.629	.000	10.948	21.799
	2	1	-16.373*	2.629	.000	-21.799	-10.948
2	1	2	14.533*	2.495	.000	9.383	19.683
	2	1	-14.533*	2.495	.000	-19.683	-9.383

Selective Stop EMG Data

Descriptive Statistics

	Mean	Std. Deviation	N
L_25_W	42.3200	18.55559	25
L_25_B	22.0000	13.12440	25
L_50_W	12.2000	18.13606	25
L_50_B	5.3200	10.86554	25
L_75_W	8.9600	6.38670	25
L_75_B	2.0400	4.74763	25
R_25_W	37.0800	18.65681	25
R_25_B	21.8800	14.19894	25
R_50_W	11.6800	13.80737	25
R_50_B	5.0000	7.30297	25
R_75_W	9.6400	7.52706	25
R_75_B	2.6400	5.26688	25

Mauchly's Test of Sphericity[a]

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
hand	1.000	.000	0	.	1.000	1.000	1.000
threshold	.714	7.753	2	.021	.778	.821	.500
button	1.000	.000	0	.	1.000	1.000	1.000
hand * threshold	.880	2.947	2	.229	.893	.960	.500
hand * button	1.000	.000	0	.	1.000	1.000	1.000
threshold * button	.927	1.744	2	.418	.932	1.000	.500
hand * threshold * button	.847	3.821	2	.148	.867	.929	.500

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
hand	Sphericity Assumed	50.430	1	50.430	.351	.559	.014
	Greenhouse-Geisser	50.430	1.000	50.430	.351	.559	.014
	Huynh-Feldt	50.430	1.000	50.430	.351	.559	.014
	Lower-bound	50.430	1.000	50.430	.351	.559	.014
Error(hand)	Sphericity Assumed	3443.820	24	143.492			
	Greenhouse-Geisser	3443.820	24.000	143.492			
	Huynh-Feldt	3443.820	24.000	143.492			
	Lower-bound	3443.820	24.000	143.492			
threshold	Sphericity Assumed	37613.527	2	18806.763	67.353	.000	.737
	Greenhouse-Geisser	37613.527	1.555	24188.167	67.353	.000	.737
	Huynh-Feldt	37613.527	1.643	22893.891	67.353	.000	.737
	Lower-bound	37613.527	1.000	37613.527	67.353	.000	.737
Error(threshold)	Sphericity Assumed	13402.973	48	279.229			
	Greenhouse-Geisser	13402.973	37.321	359.128			
	Huynh-Feldt	13402.973	39.431	339.911			
	Lower-bound	13402.973	24.000	558.457			

button	Sphericity Assumed	8268.750	1	8268.750	84.790	.000	.779
	Greenhouse-Geisser	8268.750	1.000	8268.750	84.790	.000	.779
	Huynh-Feldt	8268.750	1.000	8268.750	84.790	.000	.779
	Lower-bound	8268.750	1.000	8268.750	84.790	.000	.779
Error(button)	Sphericity Assumed	2340.500	24	97.521			
	Greenhouse-Geisser	2340.500	24.000	97.521			
	Huynh-Feldt	2340.500	24.000	97.521			
	Lower-bound	2340.500	24.000	97.521			
hand * threshold	Sphericity Assumed	143.780	2	71.890	1.399	.257	.055
	Greenhouse-Geisser	143.780	1.785	80.535	1.399	.257	.055
	Huynh-Feldt	143.780	1.919	74.919	1.399	.257	.055
	Lower-bound	143.780	1.000	143.780	1.399	.248	.055
Error(hand*threshold)	Sphericity Assumed	2465.720	48	51.369			
	Greenhouse-Geisser	2465.720	42.848	57.546			
	Huynh-Feldt	2465.720	46.059	53.534			
	Lower-bound	2465.720	24.000	102.738			
hand * button	Sphericity Assumed	57.203	1	57.203	1.654	.211	.064
	Greenhouse-Geisser	57.203	1.000	57.203	1.654	.211	.064
	Huynh-Feldt	57.203	1.000	57.203	1.654	.211	.064
	Lower-bound	57.203	1.000	57.203	1.654	.211	.064
Error(hand*button)	Sphericity Assumed	830.047	24	34.585			
	Greenhouse-Geisser	830.047	24.000	34.585			
	Huynh-Feldt	830.047	24.000	34.585			
	Lower-bound	830.047	24.000	34.585			
threshold * button	Sphericity Assumed	1976.940	2	988.470	23.884	.000	.499
	Greenhouse-Geisser	1976.940	1.864	1060.663	23.884	.000	.499
	Huynh-Feldt	1976.940	2.000	988.470	23.884	.000	.499
	Lower-bound	1976.940	1.000	1976.940	23.884	.000	.499
Error(threshold*button)	Sphericity Assumed	1986.560	48	41.387			
	Greenhouse-Geisser	1986.560	44.733	44.409			
	Huynh-Feldt	1986.560	48.000	41.387			
	Lower-bound	1986.560	24.000	82.773			
hand * threshold * button	Sphericity Assumed	106.927	2	53.463	2.686	.078	.101
	Greenhouse-Geisser	106.927	1.734	61.647	2.686	.087	.101
	Huynh-Feldt	106.927	1.858	57.559	2.686	.083	.101
	Lower-bound	106.927	1.000	106.927	2.686	.114	.101
Error(hand*threshold*button)	Sphericity Assumed	955.573	48	19.908			
	Greenhouse-Geisser	955.573	41.628	22.955			
	Huynh-Feldt	955.573	44.584	21.433			
	Lower-bound	955.573	24.000	39.816			

Significant main effect of threshold

Estimates

threshold	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	30.820	2.916	24.801	36.839
2	8.550	2.212	3.986	13.114
3	5.820	.803	4.163	7.477

Pairwise Comparisons

(I) threshold	(J) threshold	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	22.270*	2.846	.000	14.946	29.594
	3	25.000*	2.392	.000	18.843	31.157
2	1	-22.270*	2.846	.000	-29.594	-14.946
	3	2.730	1.712	.372	-1.676	7.136
3	1	-25.000*	2.392	.000	-31.157	-18.843
	2	-2.730	1.712	.372	-7.136	1.676

Significant main effect of button type

Estimates

button	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	20.313	2.167	15.841	24.786
2	9.813	1.261	7.210	12.417

Pairwise Comparisons

(I) button	(J) button	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	10.500*	1.140	.000	8.147	12.853
2	1	-10.500*	1.140	.000	-12.853	-8.147

*Significant button type * threshold interaction*

Estimates

threshold	button	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	1	39.700	3.470	32.538	46.862
	2	21.940	2.486	16.808	27.072
2	1	11.940	2.831	6.097	17.783
	2	5.160	1.725	1.600	8.720
3	1	9.300	1.232	6.758	11.842
	2	2.340	.978	.322	4.358

Pairwise Comparisons

button	(I) threshold	(J) threshold	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
1	1	2	27.760*	3.049	.000	19.914	35.606
		3	30.400*	2.492	.000	23.987	36.813
	2	1	-27.760*	3.049	.000	-35.606	-19.914
		3	2.640	2.637	.980	-4.145	9.425
	3	1	-30.400*	2.492	.000	-36.813	-23.987
		2	-2.640	2.637	.980	-9.425	4.145
2	1	2	16.780*	2.852	.000	9.440	24.120
		3	19.600*	2.644	.000	12.796	26.404
	2	1	-16.780*	2.852	.000	-24.120	-9.440
		3	2.820*	.947	.020	.383	5.257
	3	1	-19.600*	2.644	.000	-26.404	-12.796
		2	-2.820*	.947	.020	-5.257	-.383

Pairwise Comparisons

threshold	(I) button	(J) button	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
1	1	2	17.760*	1.558	.000	14.544	20.976
	2	1	-17.760*	1.558	.000	-20.976	-14.544
2	1	2	6.780*	1.555	.000	3.570	9.990
	2	1	-6.780*	1.555	.000	-9.990	-3.570
3	1	2	6.960*	1.538	.000	3.786	10.134
	2	1	-6.960*	1.538	.000	-10.134	-3.786

SSRT Analysis

Descriptive Statistics

	Mean	Std. Deviation	N
W_BISTOP_SSRT	305.3200	40.53056	25
W_LSTOP_SSRT	300.2800	38.43883	25
W_RSTOP_SSRT	306.9600	39.60375	25
B_BISTOP_SSRT	277.4800	28.92536	25
B_LSTOP_SSRT	278.4800	33.34931	25
B_RSTOP_SSRT	279.2000	29.29590	25

Mauchly's Test of Sphericity[a]

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
ButtonType	1.000	.000	0	.	1.000	1.000	1.000
StopType	.973	.624	2	.732	.974	1.000	.500
ButtonType * StopType	.928	1.721	2	.423	.933	1.000	.500

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
ButtonType	Sphericity Assumed	24961.500	1	24961.500	32.909	.000	.578
	Greenhouse-Geisser	24961.500	1.000	24961.500	32.909	.000	.578
	Huynh-Feldt	24961.500	1.000	24961.500	32.909	.000	.578
	Lower-bound	24961.500	1.000	24961.500	32.909	.000	.578
Error(ButtonType)	Sphericity Assumed	18204.000	24	758.500			
	Greenhouse-Geisser	18204.000	24.000	758.500			
	Huynh-Feldt	18204.000	24.000	758.500			
	Lower-bound	18204.000	24.000	758.500			
StopType	Sphericity Assumed	343.213	2	171.607	1.014	.370	.041
	Greenhouse-Geisser	343.213	1.948	176.197	1.014	.369	.041
	Huynh-Feldt	343.213	2.000	171.607	1.014	.370	.041
	Lower-bound	343.213	1.000	343.213	1.014	.324	.041
Error(StopType)	Sphericity Assumed	8121.120	48	169.190			
	Greenhouse-Geisser	8121.120	46.749	173.716			
	Huynh-Feldt	8121.120	48.000	169.190			
	Lower-bound	8121.120	24.000	338.380			
ButtonType * StopType	Sphericity Assumed	300.040	2	150.020	1.254	.295	.050
	Greenhouse-Geisser	300.040	1.866	160.835	1.254	.293	.050
	Huynh-Feldt	300.040	2.000	150.020	1.254	.295	.050
	Lower-bound	300.040	1.000	300.040	1.254	.274	.050
Error(ButtonType*StopType)	Sphericity Assumed	5742.960	48	119.645			
	Greenhouse-Geisser	5742.960	44.772	128.270			
	Huynh-Feldt	5742.960	48.000	119.645			
	Lower-bound	5742.960	24.000	239.290			

Significant main effect of button type

Estimates

Measure: MEASURE_1

ButtonType	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	304.187	7.689	288.317	320.056
2	278.387	5.755	266.509	290.264

Pairwise Comparisons

Measure: MEASURE_1

(I) ButtonType	(J) ButtonType	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	25.800*	4.497	.000	16.518	35.082
2	1	-25.800*	4.497	.000	-35.082	-16.518

Selective Stopping Cost

Descriptive Statistics

	Mean	Std. Deviation	N
W_LSTOP_COST	150.7200	34.99228	25
W_RSTOP_COST	154.4800	46.25934	25
B_LSTOP_COST	128.3600	33.15353	25
B_RSTOP_COST	126.6000	36.19853	25

Mauchly's Test of Sphericity

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
ButtonType	1.000	.000	0	.	1.000	1.000	1.000
StopType	1.000	.000	0	.	1.000	1.000	1.000
ButtonType * StopType	1.000	.000	0	.	1.000	1.000	1.000

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
ButtonType	Sphericity Assumed	15775.360	1	15775.360	31.064	.000	.564
	Greenhouse-Geisser	15775.360	1.000	15775.360	31.064	.000	.564
	Huynh-Feldt	15775.360	1.000	15775.360	31.064	.000	.564
	Lower-bound	15775.360	1.000	15775.360	31.064	.000	.564
Error(ButtonType)	Sphericity Assumed	12188.140	24	507.839			
	Greenhouse-Geisser	12188.140	24.000	507.839			
	Huynh-Feldt	12188.140	24.000	507.839			
	Lower-bound	12188.140	24.000	507.839			
StopType	Sphericity Assumed	25.000	1	25.000	.039	.846	.002
	Greenhouse-Geisser	25.000	1.000	25.000	.039	.846	.002
	Huynh-Feldt	25.000	1.000	25.000	.039	.846	.002
	Lower-bound	25.000	1.000	25.000	.039	.846	.002
Error(StopType)	Sphericity Assumed	15503.500	24	645.979			
	Greenhouse-Geisser	15503.500	24.000	645.979			
	Huynh-Feldt	15503.500	24.000	645.979			
	Lower-bound	15503.500	24.000	645.979			
ButtonType * StopType	Sphericity Assumed	190.440	1	190.440	.557	.463	.023
	Greenhouse-Geisser	190.440	1.000	190.440	.557	.463	.023
	Huynh-Feldt	190.440	1.000	190.440	.557	.463	.023
	Lower-bound	190.440	1.000	190.440	.557	.463	.023
Error(ButtonType*StopType)	Sphericity Assumed	8203.060	24	341.794			
	Greenhouse-Geisser	8203.060	24.000	341.794			
	Huynh-Feldt	8203.060	24.000	341.794			
	Lower-bound	8203.060	24.000	341.794			

Significant main effect of button type

Estimates

ButtonType	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	152.600	7.241	137.655	167.545
2	127.480	6.579	113.901	141.059

Pairwise Comparisons

(I) ButtonType	(J) ButtonType	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	25.120*	4.507	.000	15.818	34.422
2	1	-25.120*	4.507	.000	-34.422	-15.818

Stopping Success Rate

Descriptive Statistics

	Mean	Std. Deviation	N
W_BISTOP_RATE	62.8000	10.77033	25
W_LSTOP_RATE	63.8400	11.25344	25
W_RSTOP_RATE	62.4800	12.00389	25
B_BISTOP_RATE	59.3600	10.25865	25
B_LSTOP_RATE	57.9200	10.55904	25
B_RSTOP_RATE	58.4800	9.83667	25

Mauchly's Test of Sphericity[a]

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
ButtonType	1.000	.000	0	.	1.000	1.000	1.000
StopType	.926	1.759	2	.415	.931	1.000	.500
ButtonType * StopType	.806	4.970	2	.083	.837	.893	.500

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
ButtonType	Sphericity Assumed	743.707	1	743.707	15.499	.001	.392
	Greenhouse-Geisser	743.707	1.000	743.707	15.499	.001	.392
	Huynh-Feldt	743.707	1.000	743.707	15.499	.001	.392
	Lower-bound	743.707	1.000	743.707	15.499	.001	.392
Error(ButtonType)	Sphericity Assumed	1151.627	24	47.984			
	Greenhouse-Geisser	1151.627	24.000	47.984			
	Huynh-Feldt	1151.627	24.000	47.984			
	Lower-bound	1151.627	24.000	47.984			
StopType	Sphericity Assumed	9.333	2	4.667	.832	.441	.033
	Greenhouse-Geisser	9.333	1.863	5.010	.832	.434	.033
	Huynh-Feldt	9.333	2.000	4.667	.832	.441	.033
	Lower-bound	9.333	1.000	9.333	.832	.371	.033
Error(StopType)	Sphericity Assumed	269.333	48	5.611			
	Greenhouse-Geisser	269.333	44.709	6.024			
	Huynh-Feldt	269.333	48.000	5.611			
	Lower-bound	269.333	24.000	11.222			
ButtonType * StopType	Sphericity Assumed	42.293	2	21.147	3.898	.027	.140
	Greenhouse-Geisser	42.293	1.675	25.257	3.898	.035	.140
	Huynh-Feldt	42.293	1.786	23.686	3.898	.032	.140
	Lower-bound	42.293	1.000	42.293	3.898	.060	.140
Error(ButtonType*StopType)	Sphericity Assumed	260.373	48	5.424			
	Greenhouse-Geisser	260.373	40.189	6.479			
	Huynh-Feldt	260.373	42.854	6.076			
	Lower-bound	260.373	24.000	10.849			

Significant main effect of button type

Estimates

ButtonType	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1	63.040	2.238	58.420	67.660
2	58.587	2.008	54.443	62.731

Pairwise Comparisons

(I) ButtonType	(J) ButtonType	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	4.453*	1.131	.001	2.119	6.788
2	1	-4.453*	1.131	.001	-6.788	-2.119